Project-X Workshop Summary

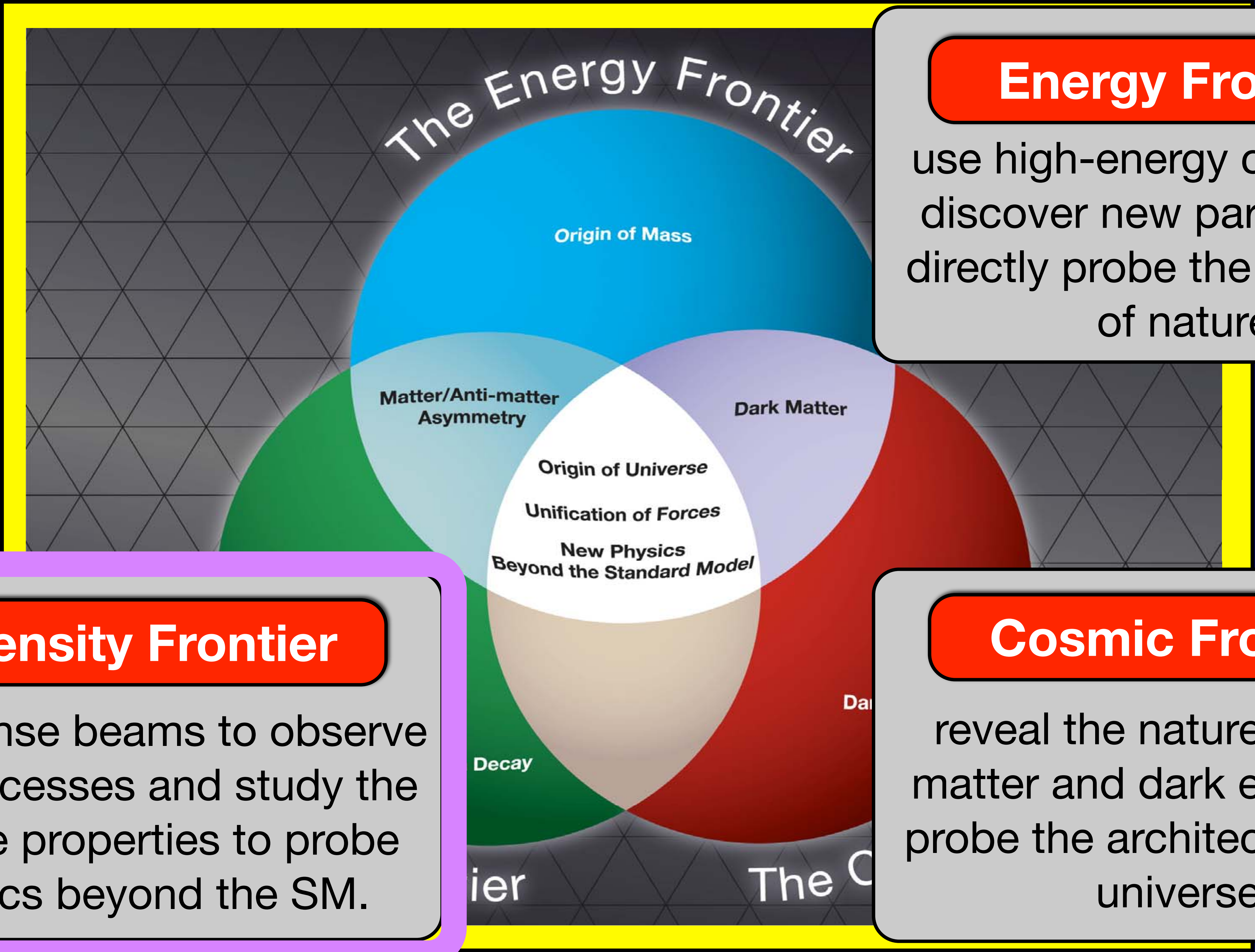
Yoshitaka Kuno
Department of Physics
Osaka University

November 10th, 2009
Project-X Workshop
at Fermi National Laboratory

Outline

- Introduction
- Neutrinos
- Muons
- Kaons
- Standard Model via Nuclear Physics
- Summary

Tools :
The Three Frontiers of Particle Physics



Energy Frontier

use high-energy colliders to discover new particles and directly probe the properties of nature

Intensity Frontier

use intense beams to observe rare processes and study the particle properties to probe physics beyond the SM.

Cosmic Frontier

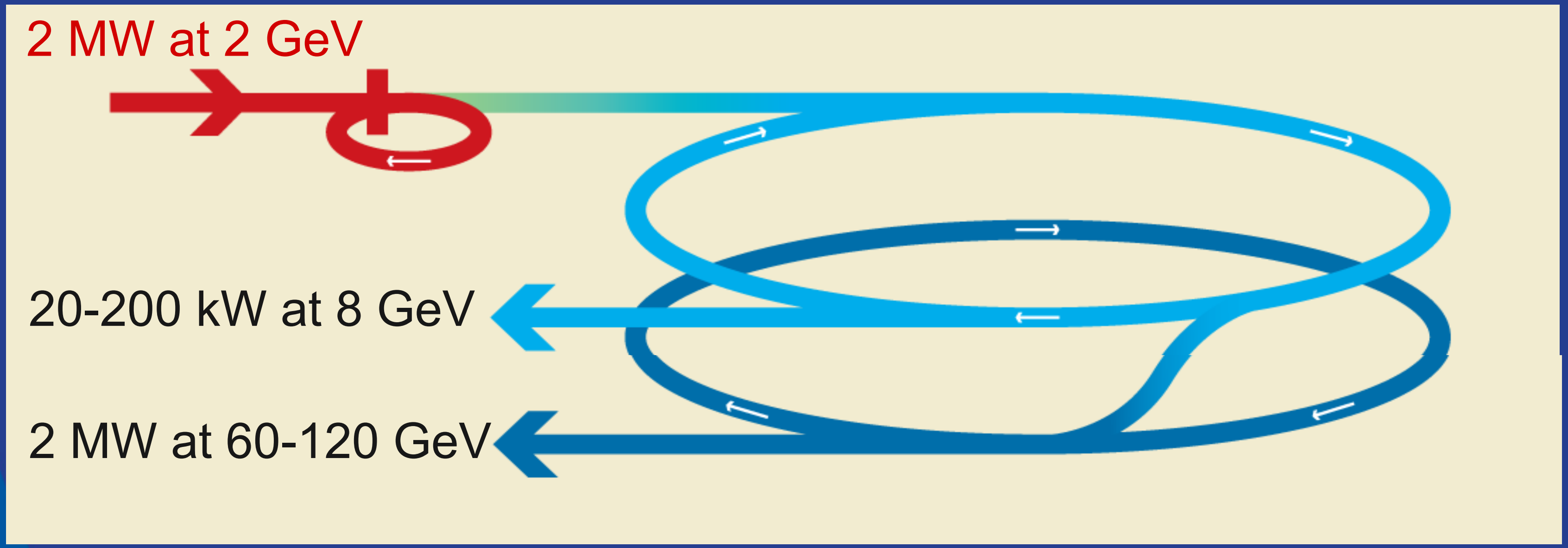
reveal the natures of dark matter and dark energy and probe the architecture of the universe.

from C. Baltay's talk at the P5 meeting, 29 May 2008

Project-X IC2

Evolution of Project X: 3 Simultaneous Beams

- 2 MW CW (continuous pulses at 325 MHz) 2^{+} GeV protons
  - rare processes and precision measurements
  - flexible time patterns and pulse intensities
- 20 – 200 kW 8 GeV protons
  - rare processes and precision measurements
- 2 MW 60 – 120 GeV protons (to Homestake) for neutrinos



NEUTRINOS

Features of Neutrino Physics at Project-X

- High beam power from Project-X is needed.
- A wide band beams to observe oscillation peaks
- Large detectors at DUCEL

Neutrino Mixing Matrix

$$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Atmos. L/E $\mu \to \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \to \mu, \tau$ $0\nu\beta\beta$ decay

500km/GeV 15km/MeV

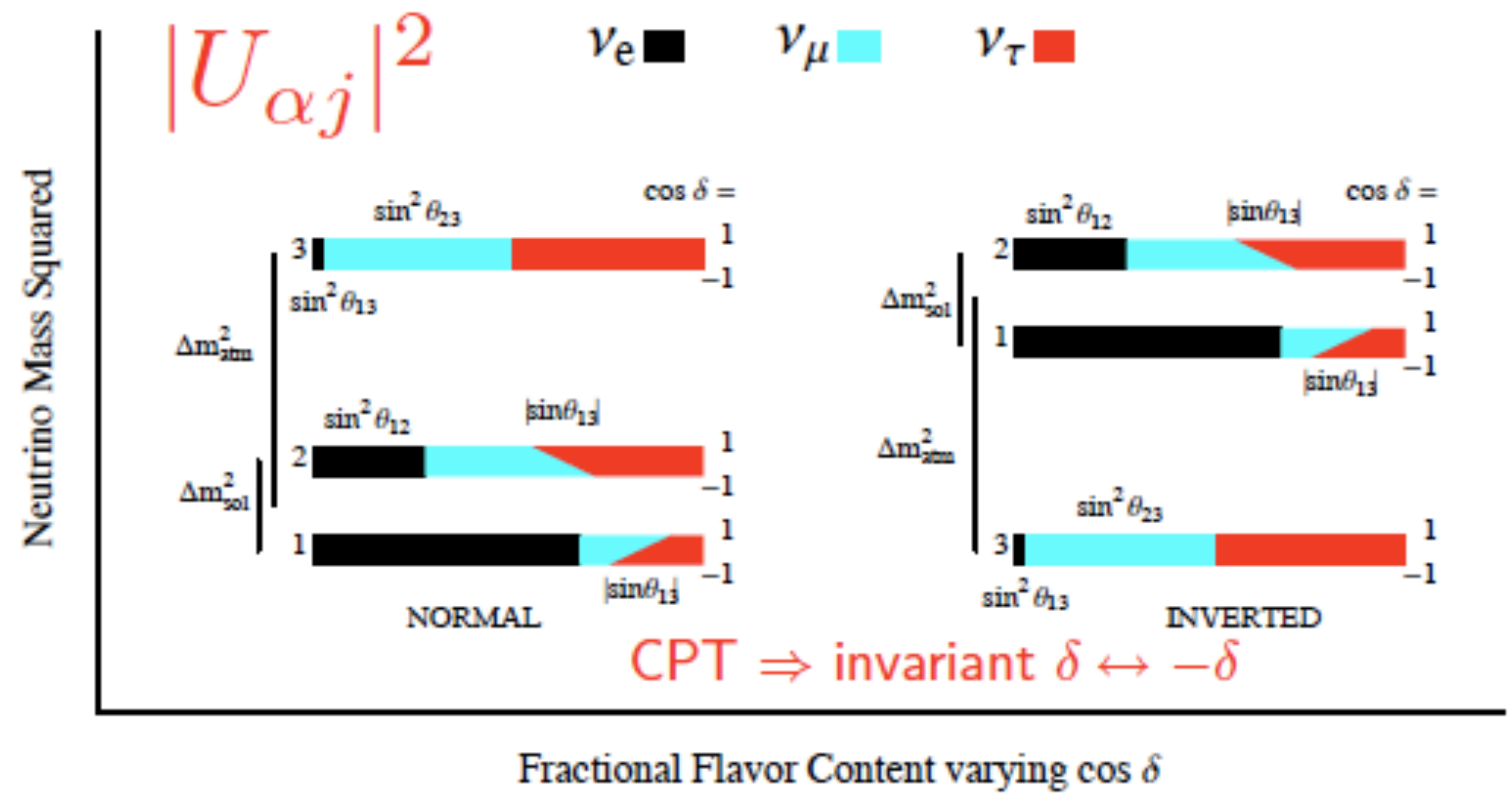
solar/KamLAND

Reactor/LBL

$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Atmospheric Nus

Neutrino Mixing and Mass Ordering



$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2 \qquad \sin^2\theta_{12} \sim 1/3$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2 \qquad \sin^2\theta_{23} \sim 1/2$$

$$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03 \qquad \sin^2\theta_{13} < 3\%$$

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e \qquad 0 \leq \delta < 2\pi$$

Neutrinos and the Standard Model

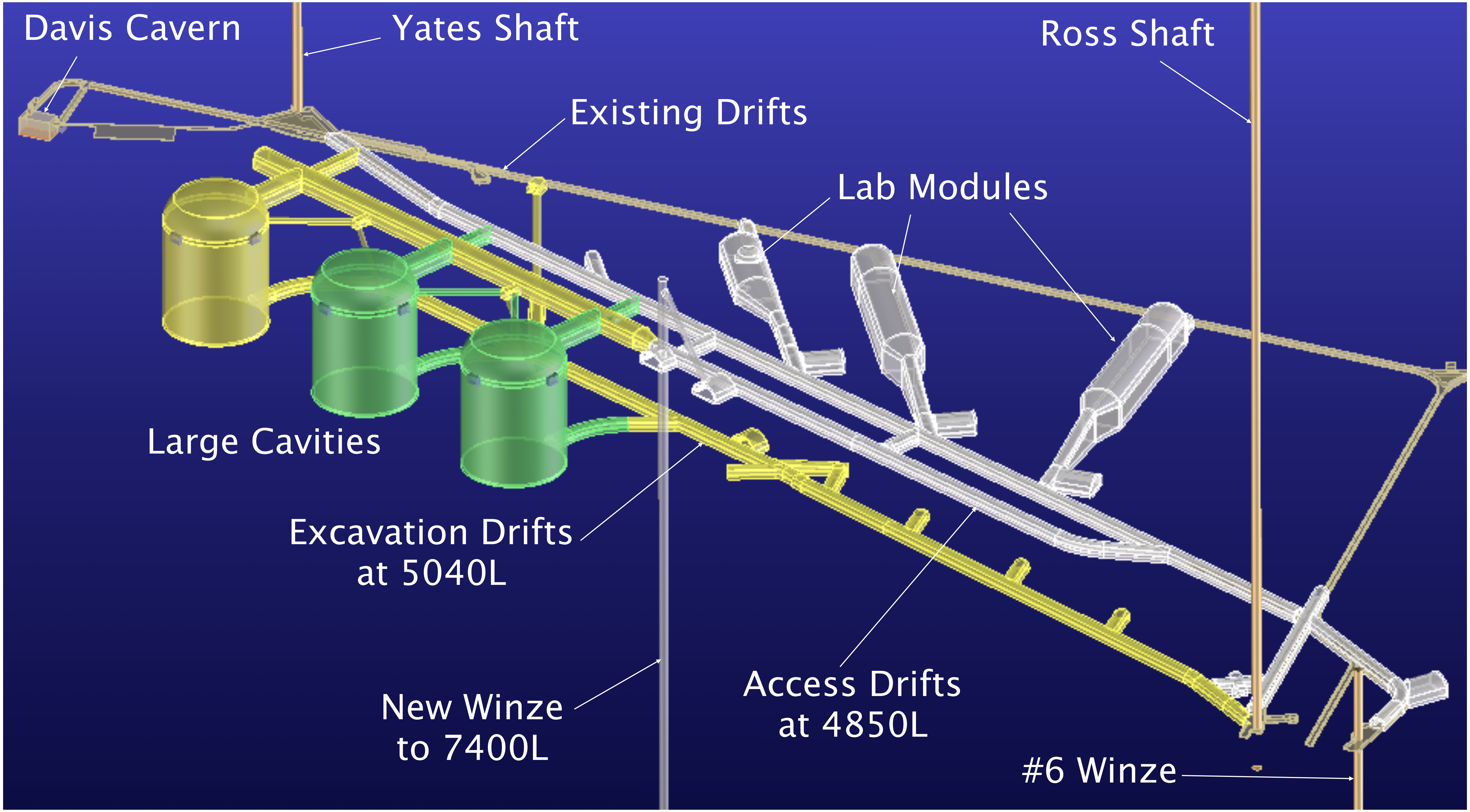
Massive neutrinos have several implications beyond just lepton flavor oscillations:

- Neutrinos may have a non-zero magnetic moment.
- Heavier neutrinos could decay into lighter ones
- They will have an effect on the CMB spectrum
- CP violation in early universe?
- Hint of unification scale below GUTs

Neutrino Facility at Fermilab

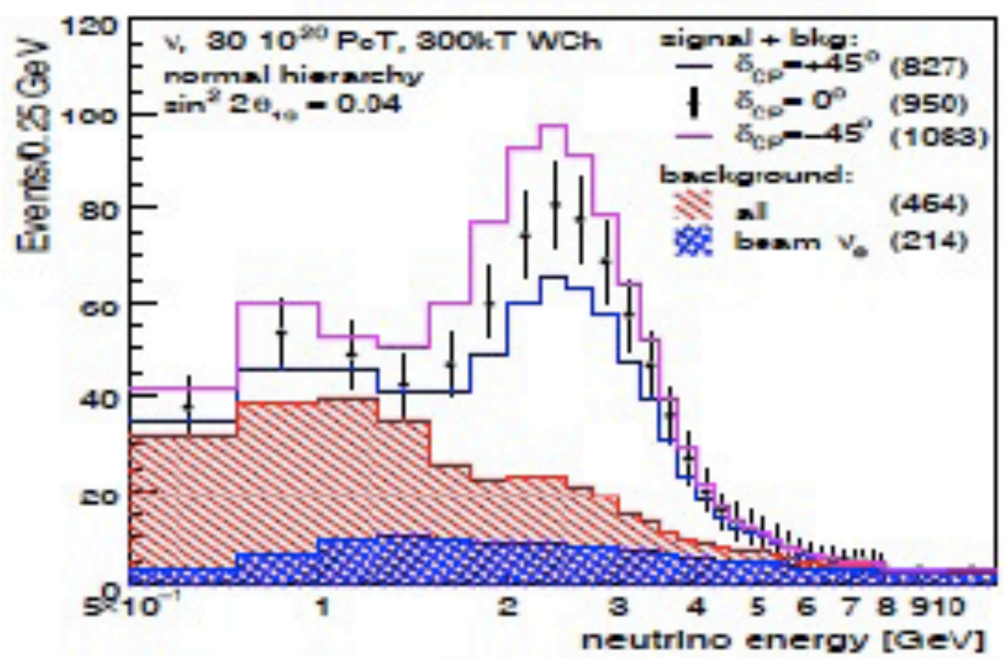
Target Hall + Decay Pipe + Absorber + Near Detector Hall

Excavation Plans
October 09

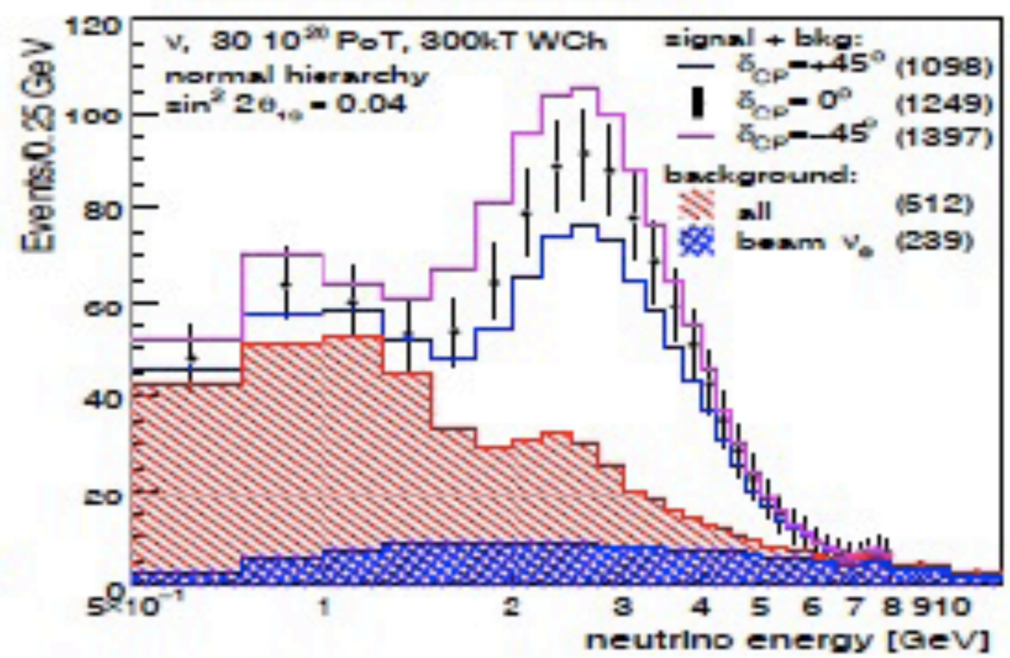


Water Cerenkov spectra for NuMI-like beams
with a 280m DP length

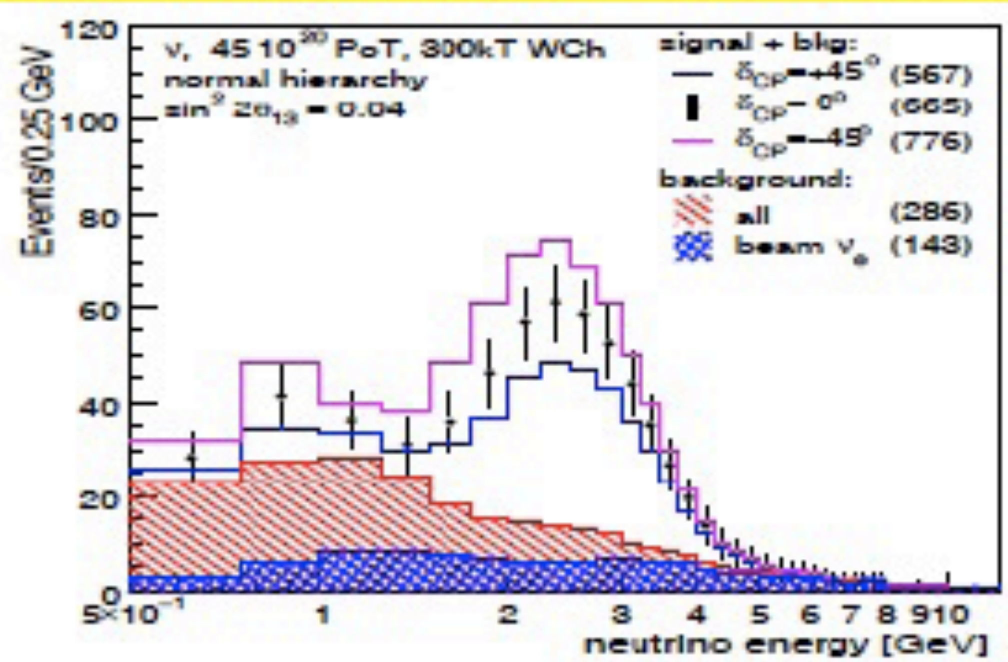
120 GeV, 250kA



120 GeV, 350kA



60 GeV, 250kA, 0.75× beam power

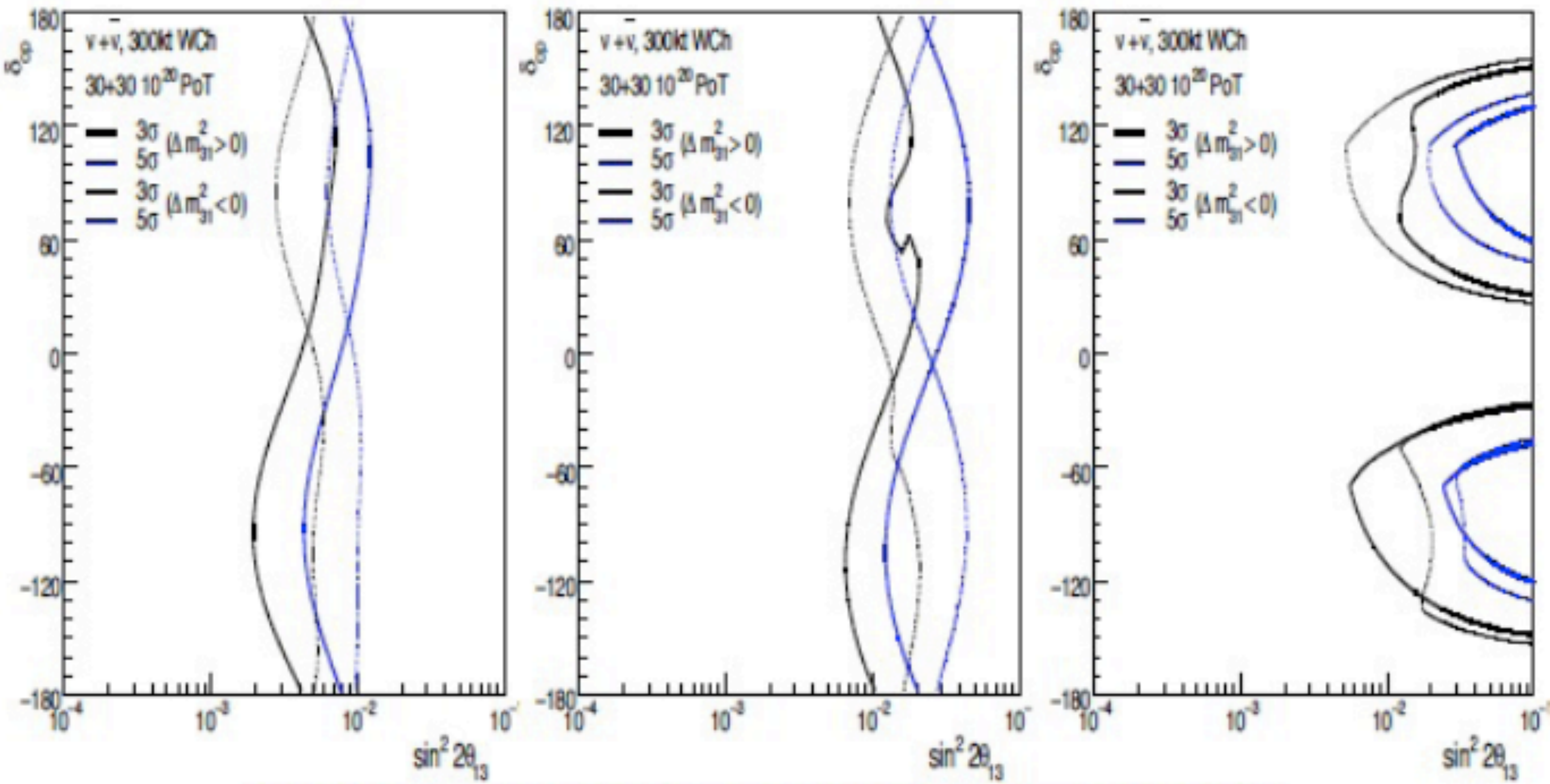


Sensitivities for various NuMI-like beam options

with a 280m DP length

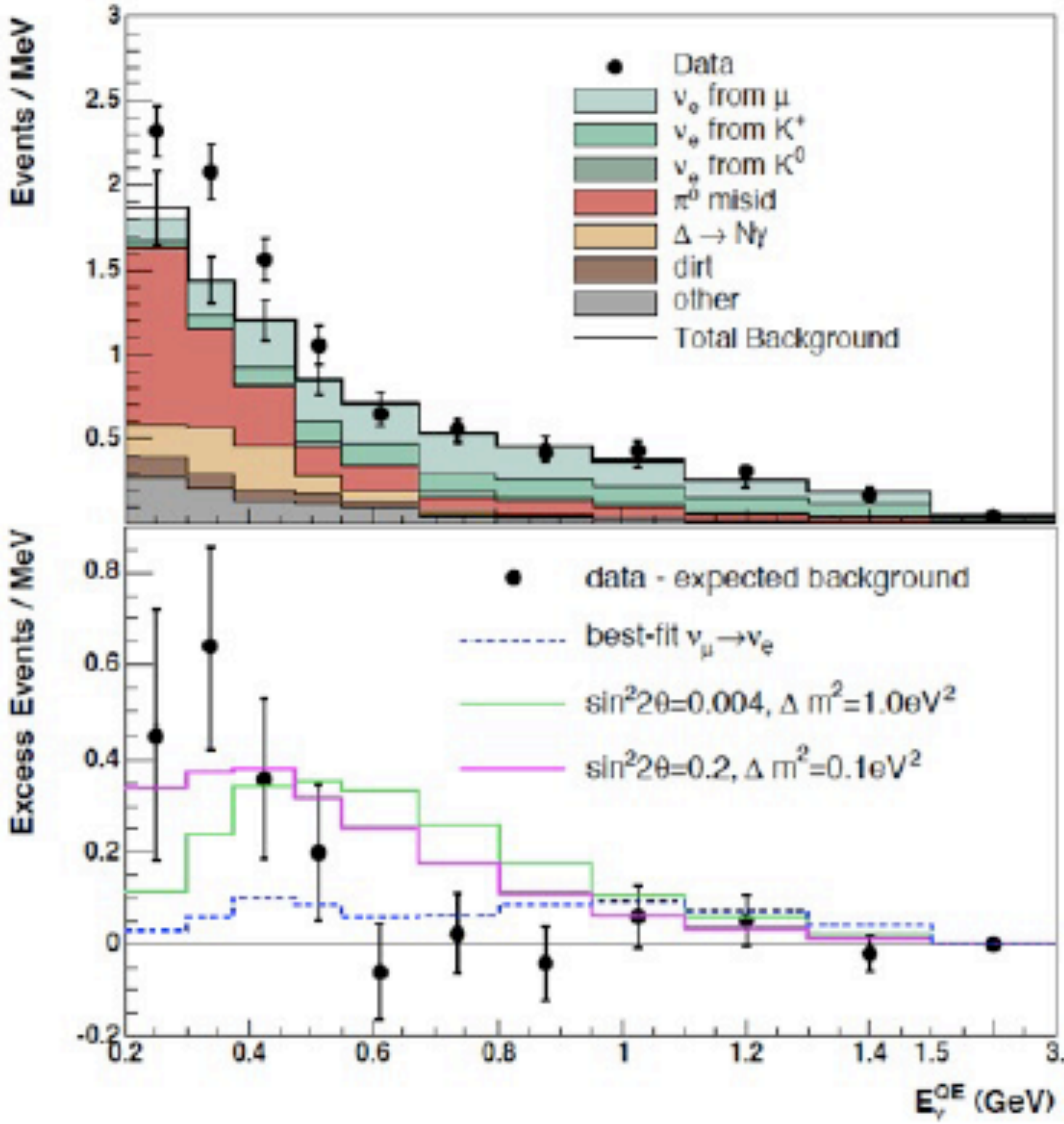
Mark Dierckxsens

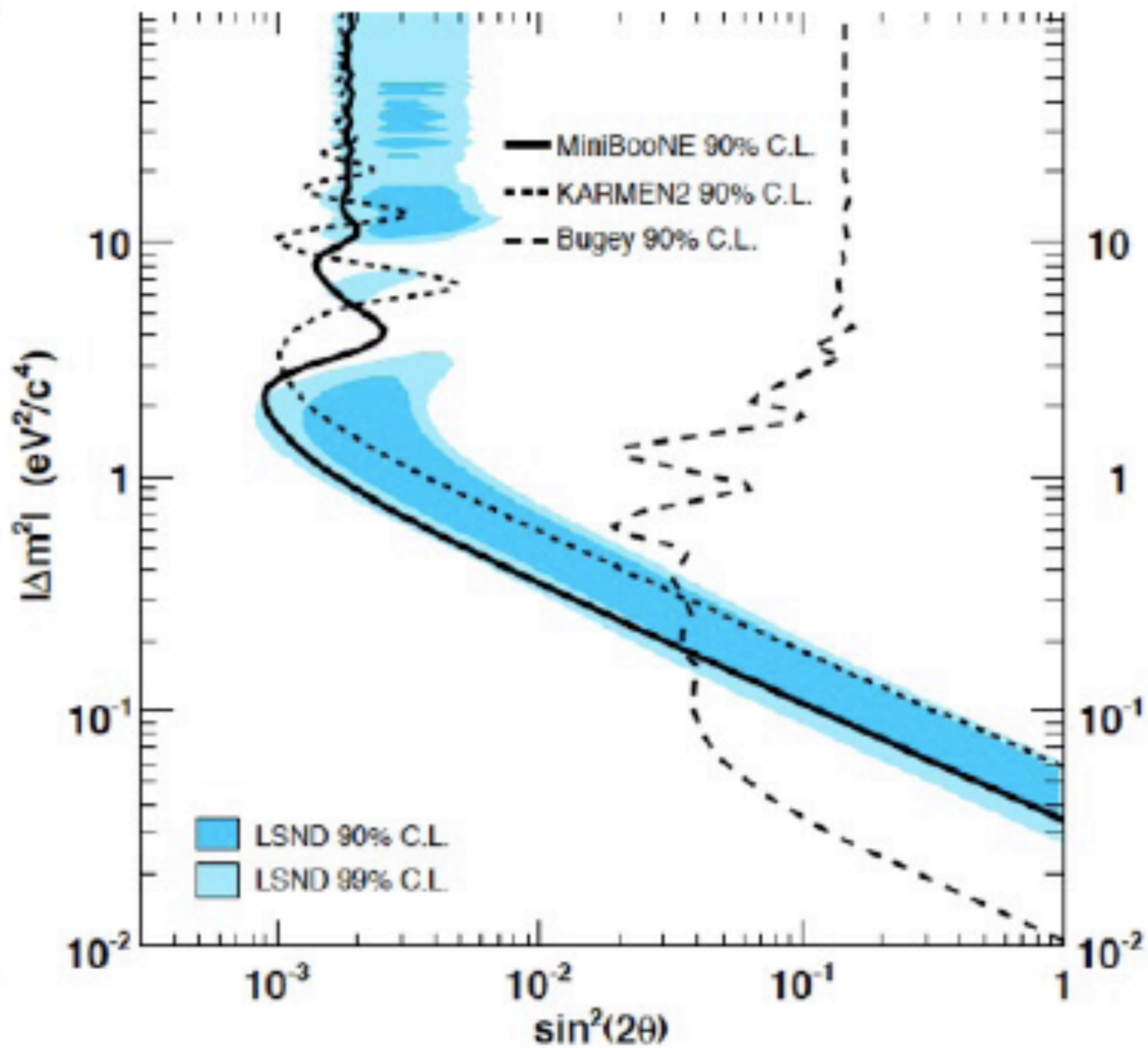
$\sin^2 2\theta_{13} \neq 0$ | mass hierarchy | $\delta_{cp} \neq 0, \pi$



Default: 120 GeV, 250kA, no plug, 3+3 MW.yr

MiniBooNE
What produced the excess seen by LSND?



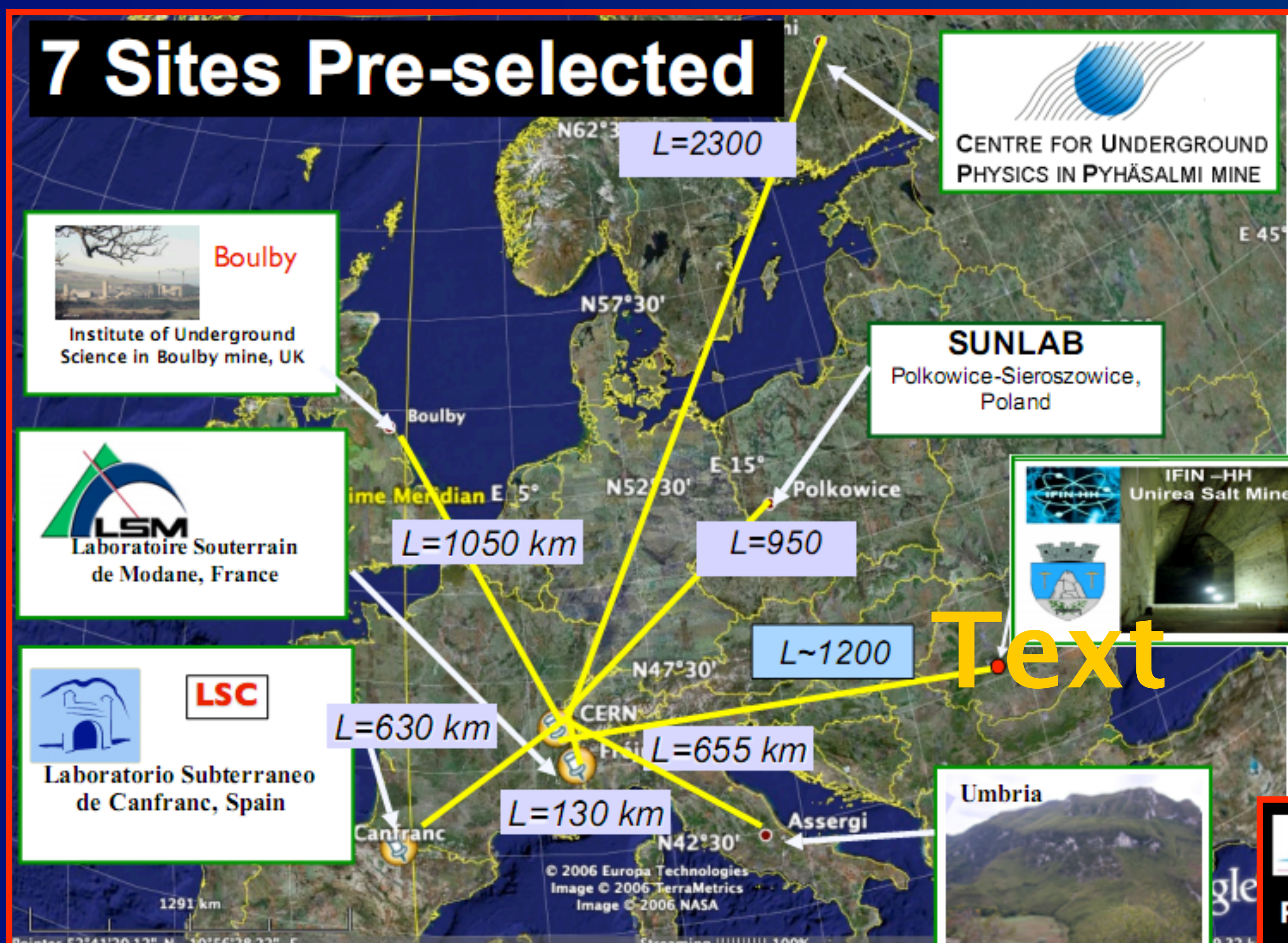


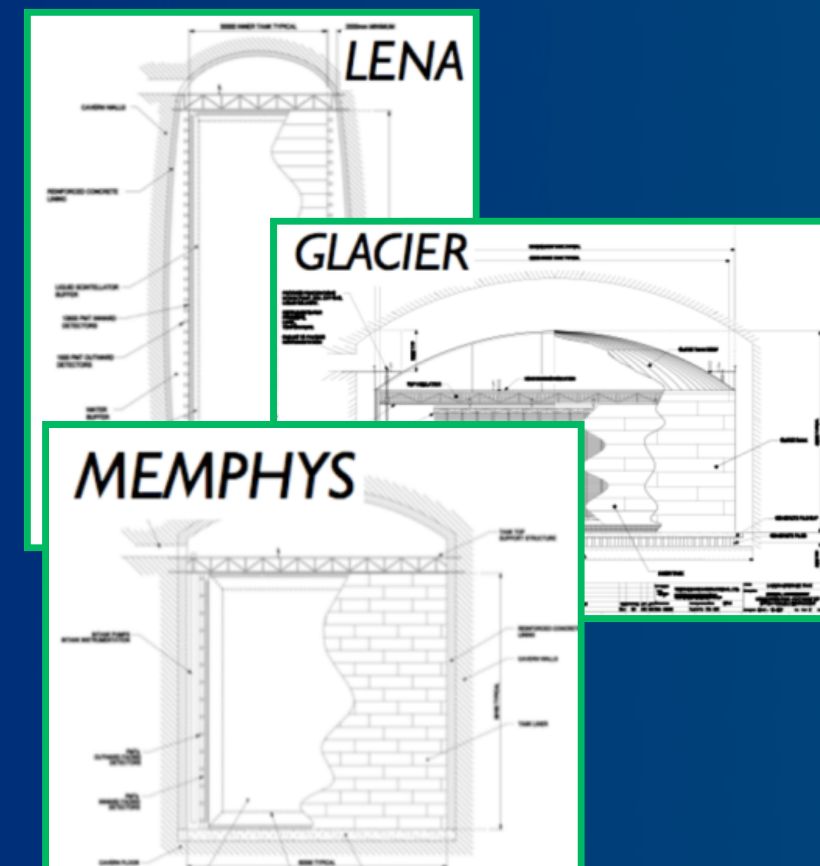
- Not conventional neutrino oscillations (98% CL)
- Low energy excess remains unexplained

New Physics in Neutrino Physics

- Possible signals of new physics in the neutrino sector:
  - Non-standard interactions
  - Non-unitary mixing
  - Mixing with sterile neutrinos
- High-intensity neutrino beams can significantly improve bounds, but discoveries still require very large new physics effects
- Another use of future neutrino detectors:
  Search for light, long-lived hidden sector particles ($\rightarrow$ Dark Matter?)
- An interesting near-future possibility: Emulsion Cloud Chamber (ν_τ detector) in the NuMI beam
  - Sensitive to non-standard decay $\pi \rightarrow \nu_\tau$ (down to BR $< 10^{-6}$)
  - ν_τ detection desirable for optimum coverage of flavor space

Search for European Deep Underground Lab Site





1. **Seven sites preselected**
2. **Consideration of three technolog**
   1. **Water Cherenkov (Memphys)**
   2. **Liquid argon (Glacier)**
   3. **Liquid scintilator (LENA)**

LAGUNA - A Clear Timeline

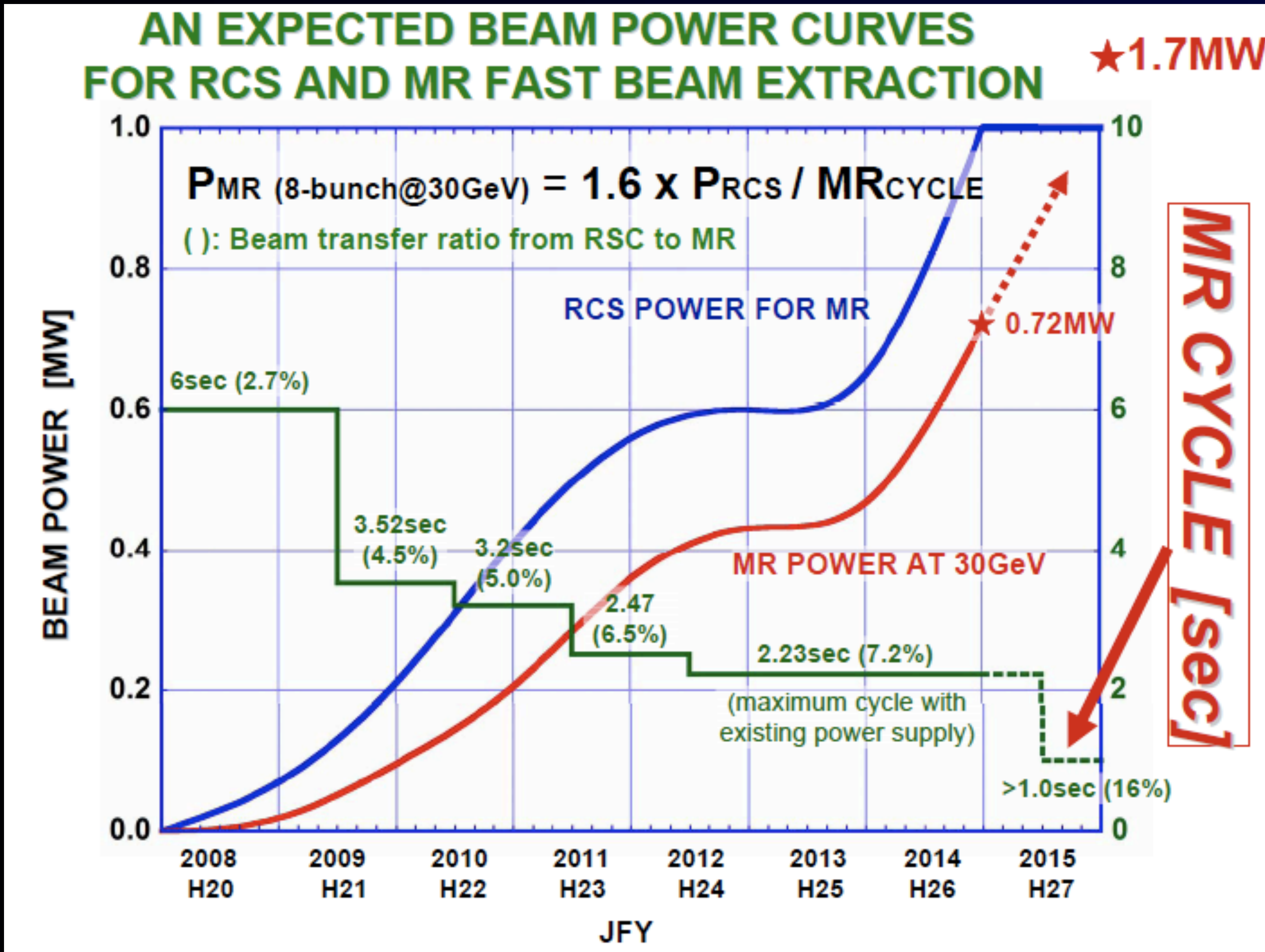
Paper Design Study (EU funded):	2008-2010
Prioritize the sites and down-select:	July 2010
Prioritize detectors and down-select LAGUNA-NEXT:	2011-2012
Detailed construction phase study:	2012-2015
LAGUNA construction	>2015

well matched to new CERN neutrino beam in 10 years?

Boulby (UK)
Canfranc (Spain)
Frejus (France)
Phyasalmi (Finland)
Sieroszowice (Poland)
Slanic (Romania)
Umbria (Italy)

Glacier (liquid argon)
Lena (liquid scintillator)
Memphys (liquid water)

J-PARC Future Plan for Improvement of Fast Beam Extraction



MUONS

Features of Muon Physics at Project-X

- High beam power (~2 MW) from Project-X to produce enoumous number of muons
- a (potential) capability to manipulate different beam time strucutre
  - from CW to pulsed (of 1kHz)

Why Muons ?

Guidelines for Rare Process Searches

(1) Many particles are needed. More is better.

The muon is the lightest unstable particle and therefore given energy more muons can be produced.

(2) Backgrounds in theoretical & experimental should be less.

The muon does not have strong interaction, and therefore the processes with muons are theoretically clean.

List of cLFV Processes with Muons

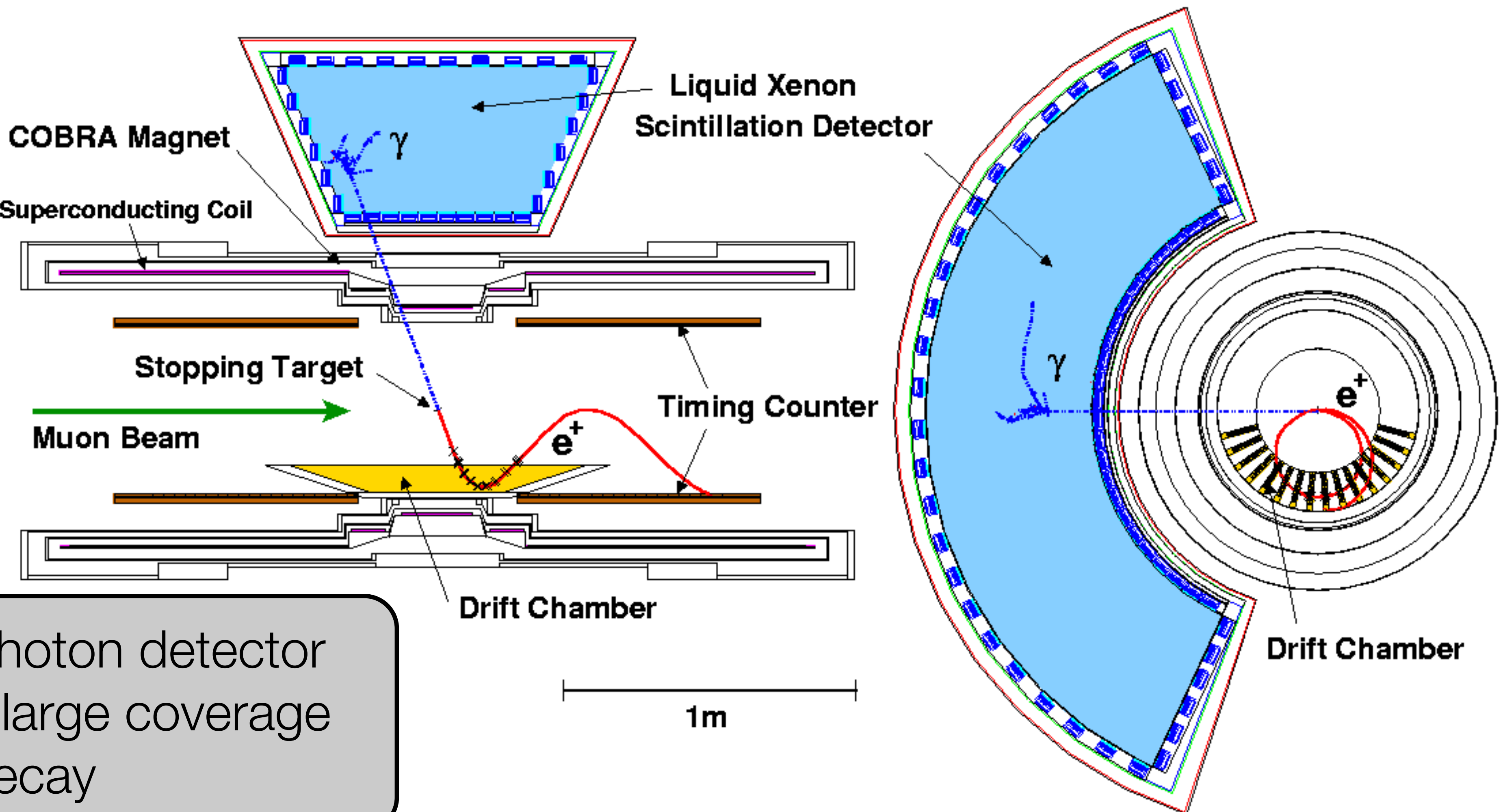
ΔL=1

- $\mu^+ \rightarrow e^+\gamma$
- $\mu^+ \rightarrow e^+e^+e^-$
- $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$
- $\mu^- + N(A,Z) \rightarrow e^+ + N(A,Z-2)$

ΔL=2

- $\mu^+e^- \rightarrow \mu^-e^+$
- $\mu^- + N(A,Z) \rightarrow \mu^+ + N(A,Z-2)$
- $\nu_\mu + N(A,Z) \rightarrow \mu^+ + N(A,Z-1)$
- $\nu_\mu + N(A,Z) \rightarrow \mu^+\mu^+\mu^- + N(A,Z-1)$

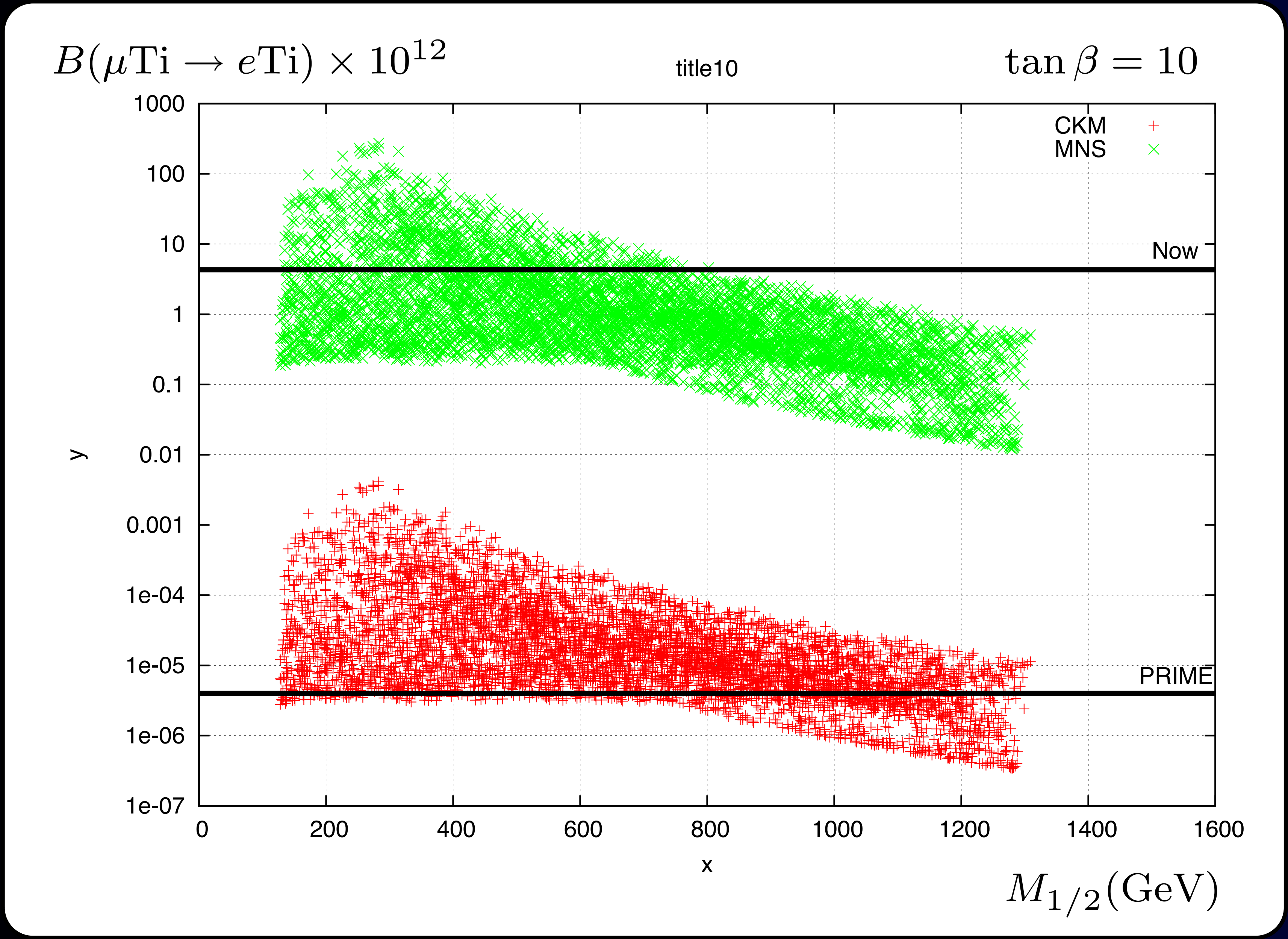
MEG and its Upgrade



- Improvement of photon detector
  - small PMT and large coverage
- Polarized muon decay

- **Muon beam up to 10^8/sec**
  - Acceptance ~10%
  - DAQ time 2-3x10^7sec
- Xenon detector
  - Resolution
  - pile-up rejection
- Positron spectrometer
  - resolution

Why Muon to Electron Conversion at a Sensitivity of $<10^{-18}$?



Calibbi, Faccia, Masiero, Vempati, hep-ph/0605139

BR~10^{-18}

Full coverage of SUSY parameter space can be made.

Further Background Rejection to < 10^{-18}

mono-energetic muon beam

Muon DIO & Beam flush → narrow muon beam spread — 1/10 thickness muon stopping target

pure muon beam

Pion background → long muon beam-line — muon storage ring

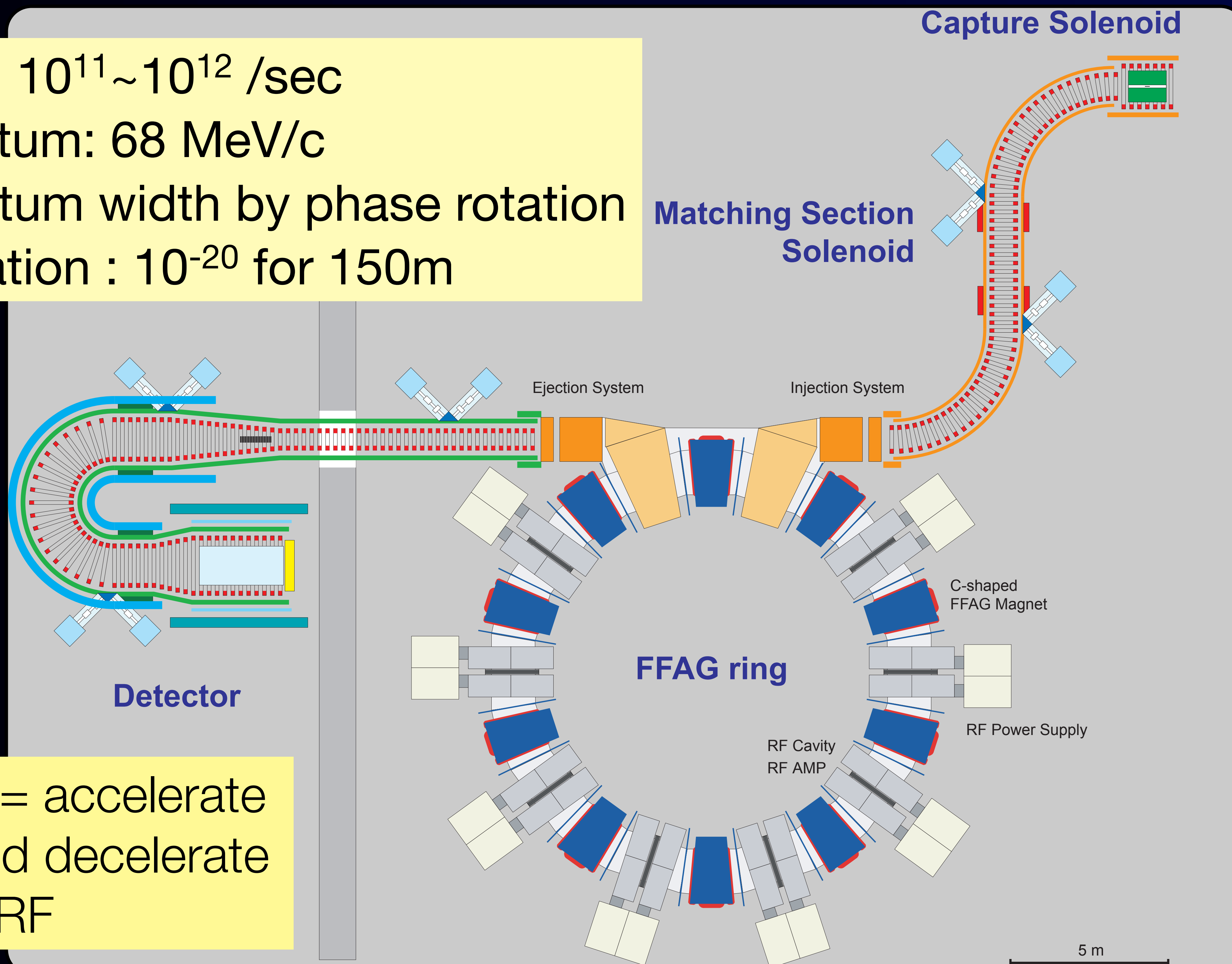
Beam-related Background → Extinction at muon beam — fast kickers

Cosmic-ray background → low-duty running — 100 Hz rather than 1 MHz

PRISM Muon Beam

PRISM=Phase Rotated Intense Slow Muon source

muon intensity: 10^{11}~10^{12} /sec
central momentum: 68 MeV/c
narrow momentum width by phase rotation
pion contamination : 10^{-20} for 150m



Phase rotation = accelerate slow muons and decelerate fast muons by RF

My previous Project X Workshop Summary for g-2

E821 final error:

± 0.48 ppm statistical

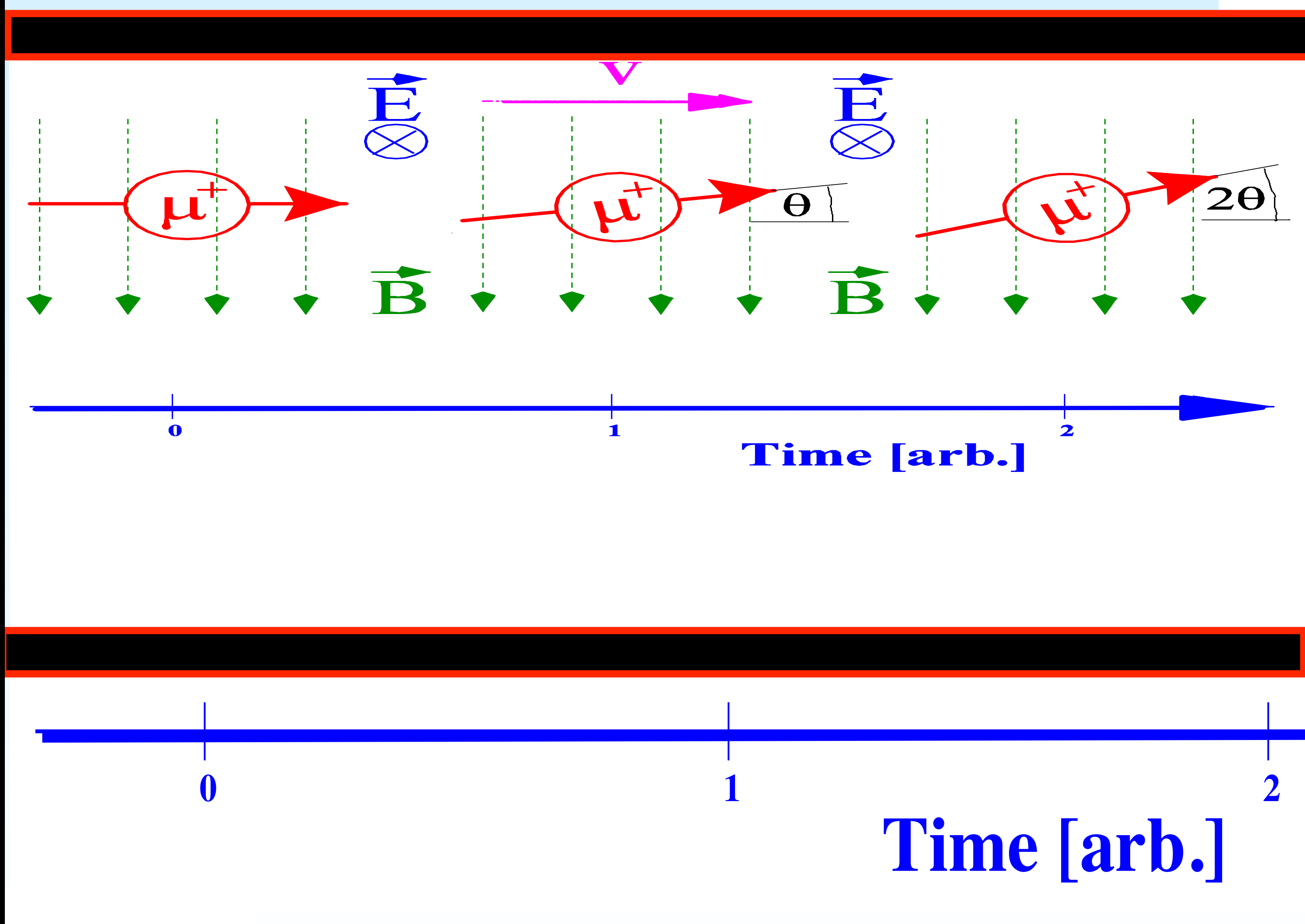
± 0.27 ppm systematic

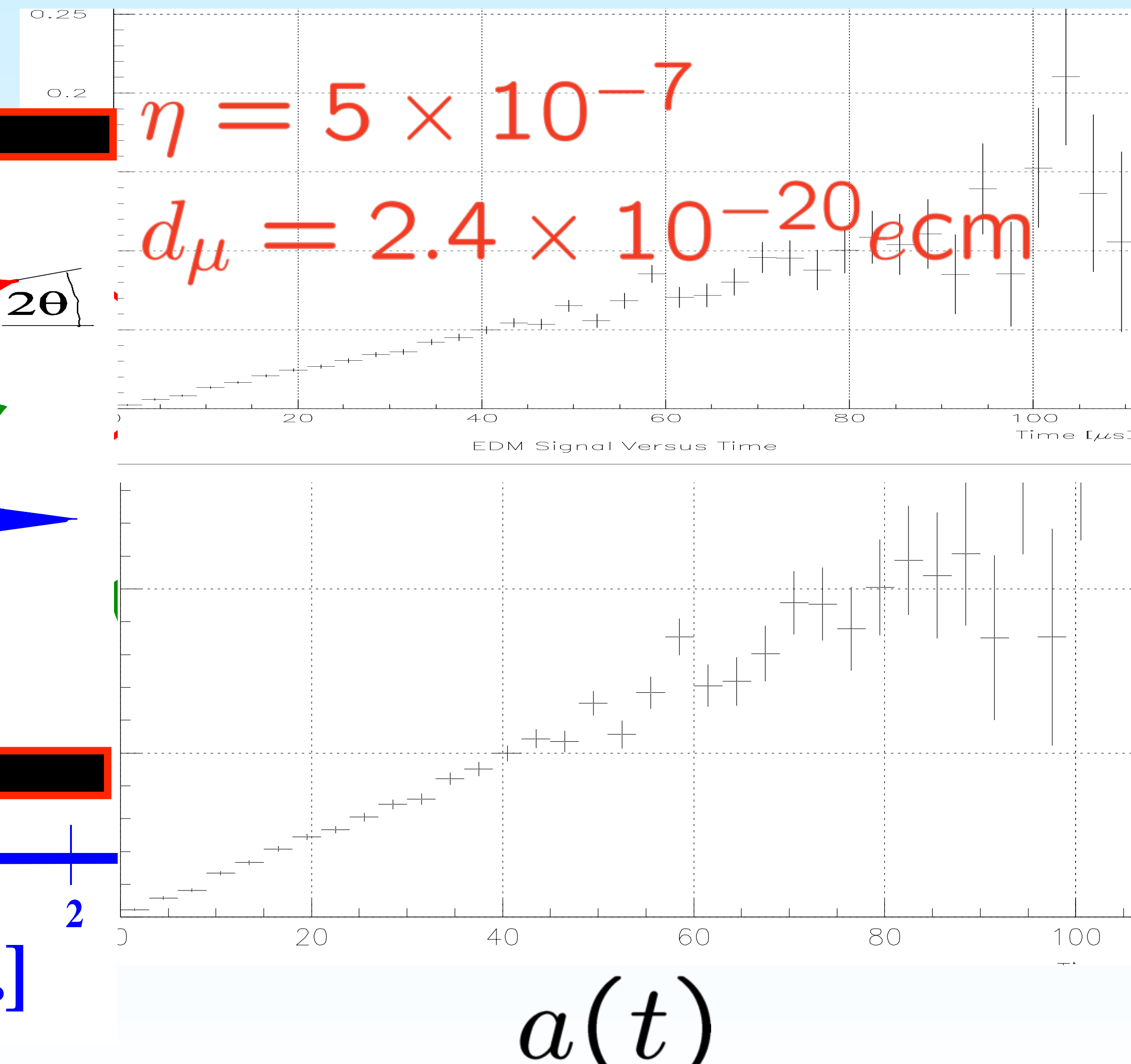
Discussion: Three Phases for FNAL implementation

- **Phase 1:** μ^+ measurement to 0.1 ppm statistical
  - Requires Nova type upgrades, beam manipulations and ~4x10^{20} p
  - Can do in ***pre Project X era***
- **Phase 2:** μ^- measurement to 0.1 ppm (or lower)
  - Requires ~2-3 x more protons due to lower π^- cross section
  - Would ***benefit from Project X***
- **Phase 3:** All "integrating" with much higher proton beam and restricted storage ring acceptance to lower systematics
  - ***Requires Project X***

"Frozen spin" technique to measure EDM

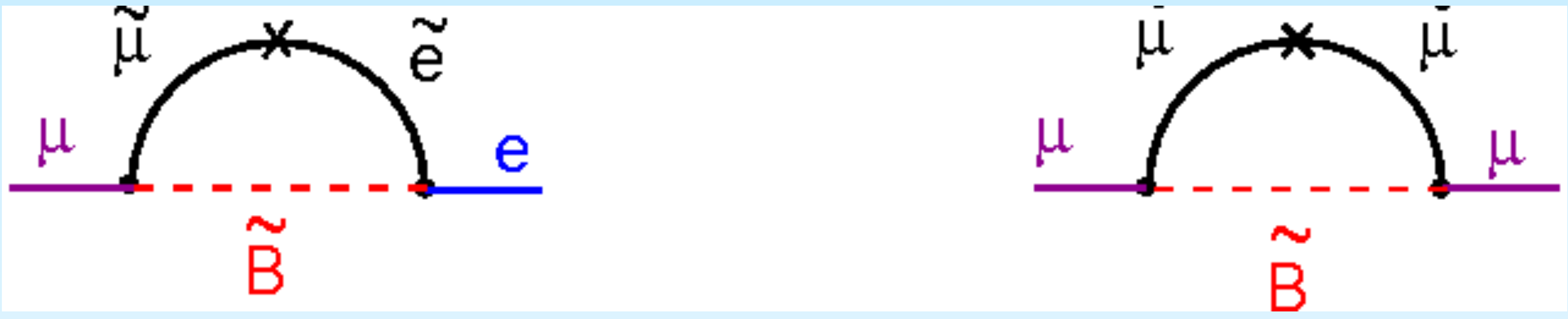
- Turn off the (g-2) precession with radial **E** Up-Down detectors measure EDM asymmetry
- Look for an up-down asymmetry building up with time
- Side detectors measure (g-2) precession cancellation
  - To prove the spin is frozen





Connection between MDM, EDM and the lepton flavor violating transition moment $\mu \rightarrow e$

SUSY $\Rightarrow$ slepton mixing **MDM, EDM**



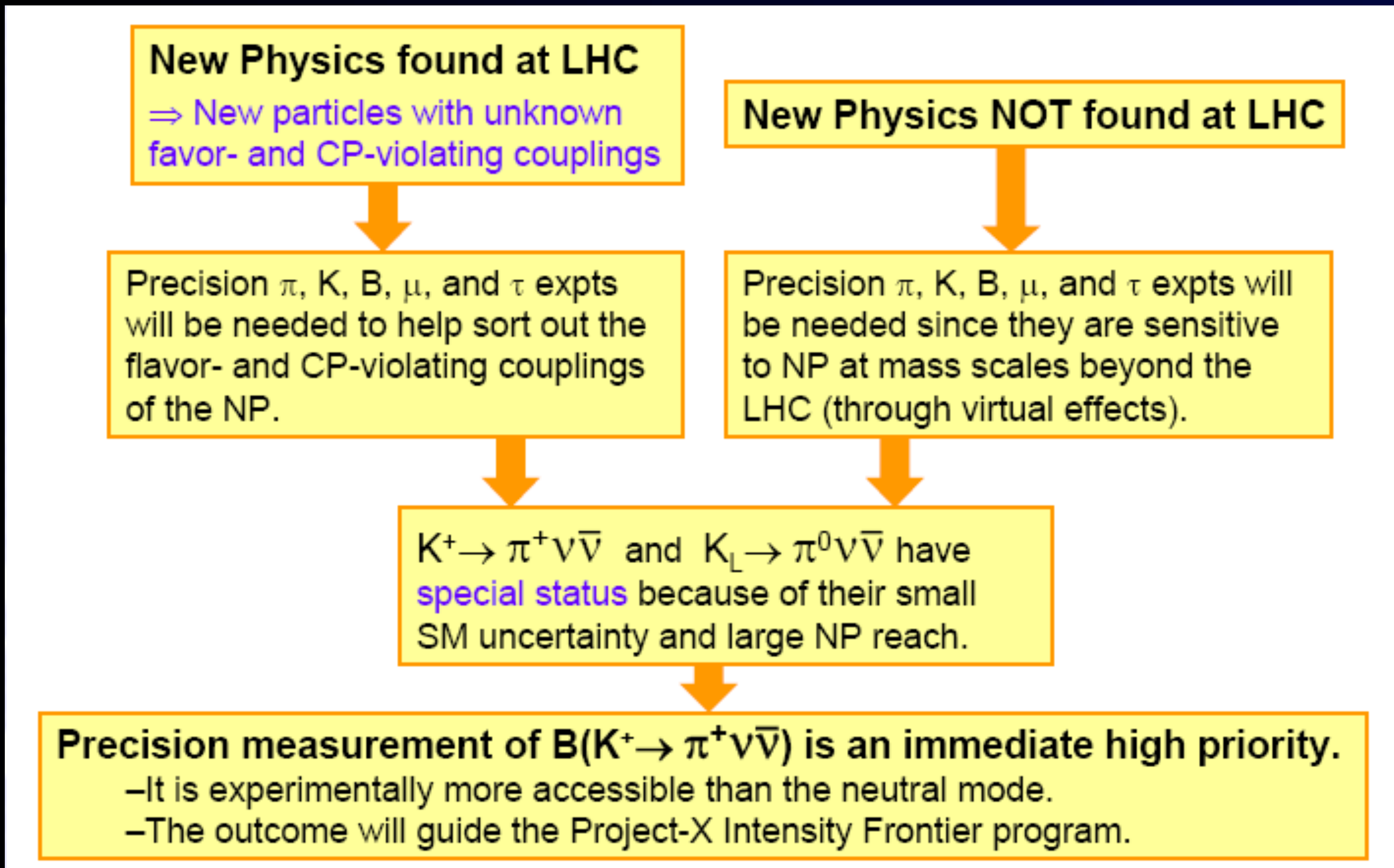
$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

KAONS

Features of Kaon Physics at Project-X

- a CW beam would be required to kaon physics
- a TOF neutral K beam is unique to carry out $K_L \rightarrow \pi\nu\nu$

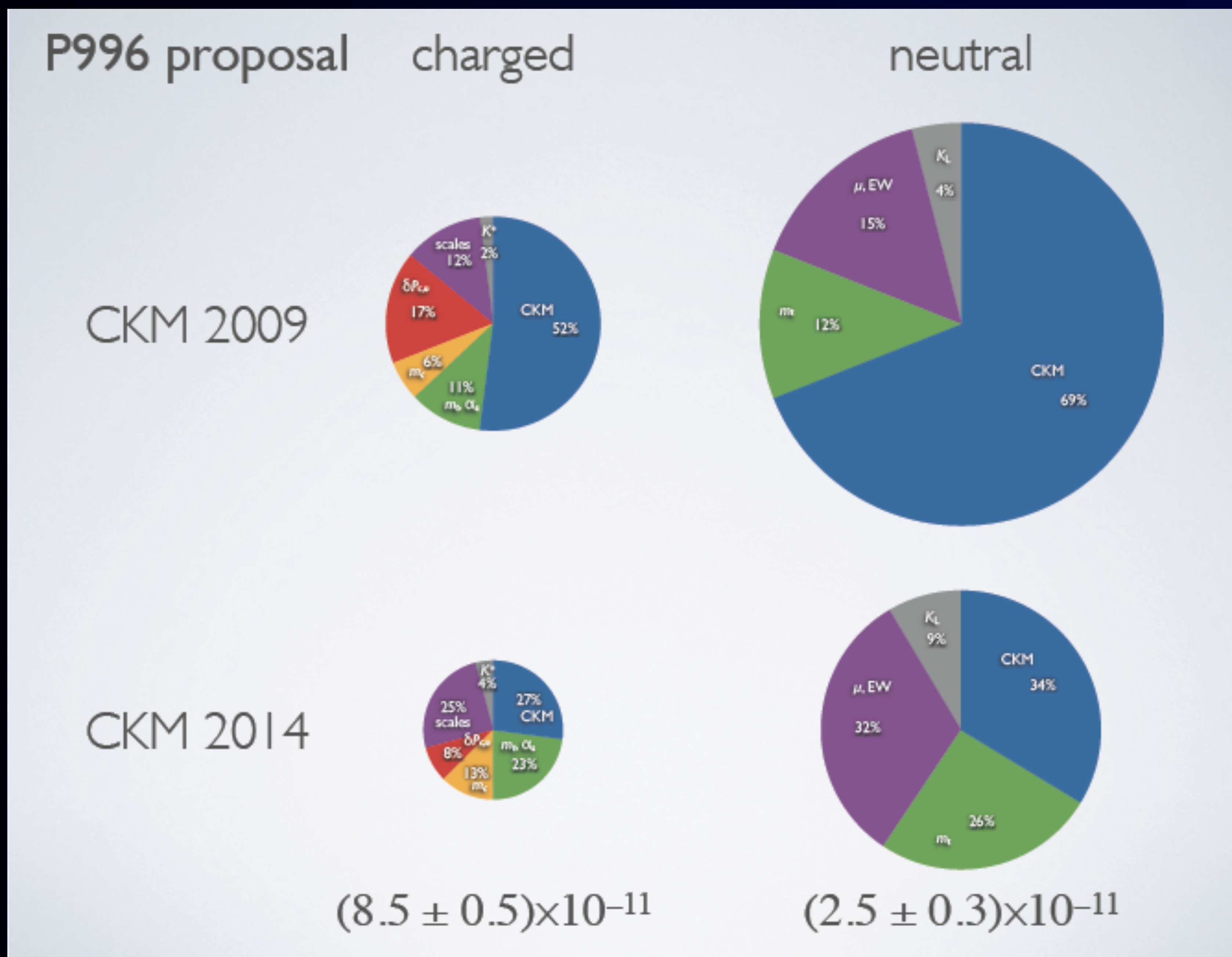
Flavor Physics at the LHC Era



Richie

K→πνν Theory Developments:

Charged mode better controlled than neutral-mode !



Kronfeld

Sensitivity of Kaon Physis Today

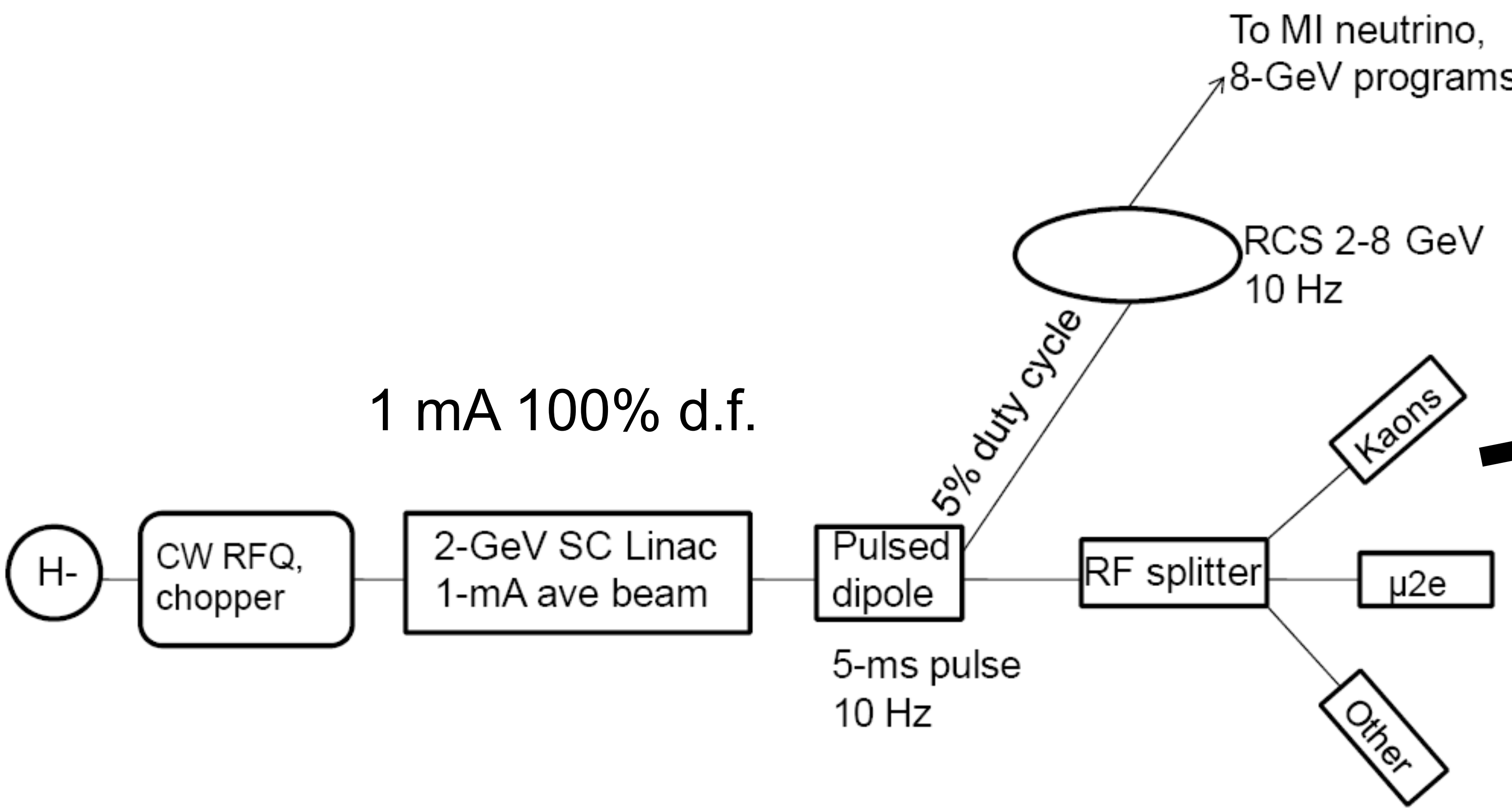
- CERN NA62: 100×10^{-12} measurement sensitivity of $K^+ \rightarrow e^+ \nu$
- Fermilab KTeV: 20×10^{-12} measurement sensitivity of $K_L \rightarrow \mu\mu ee$
- Fermilab KTeV: 20×10^{-12} search sensitivity for $K_L \rightarrow \pi\mu e$, $\pi\pi\mu e$
- BNL E949: 20×10^{-12} measurement sensitivity of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$
- BNL E871: 2×10^{-12} measurement sensitivity of $K_L \rightarrow e^+ e^-$
- BNL E871: 1×10^{-12} search sensitivity for $K_L \rightarrow \mu e$

Probing new physics above a 10 TeV scale with 20-50 kW of protons.

Next goal: 1000-event $\pi\nu\nu$ experiments...10^{-14} sensitivty.

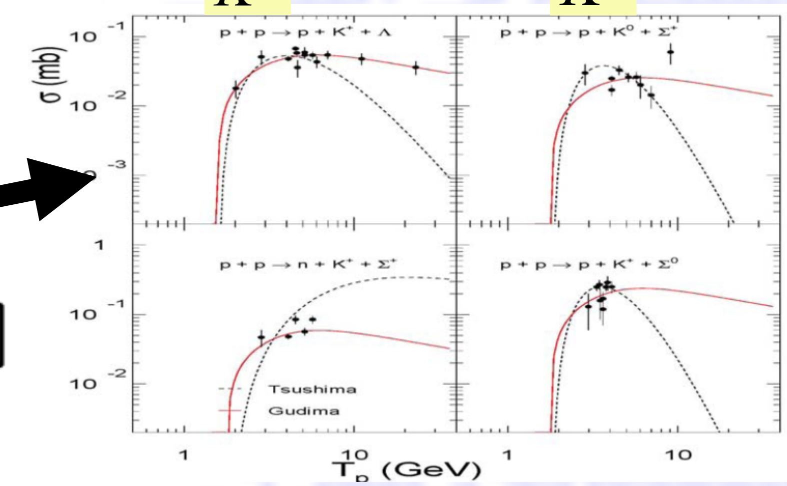
The road to much higher beam power:

Project X ICD-2



Kaon Production *vs.* T_P

K^+ K^0



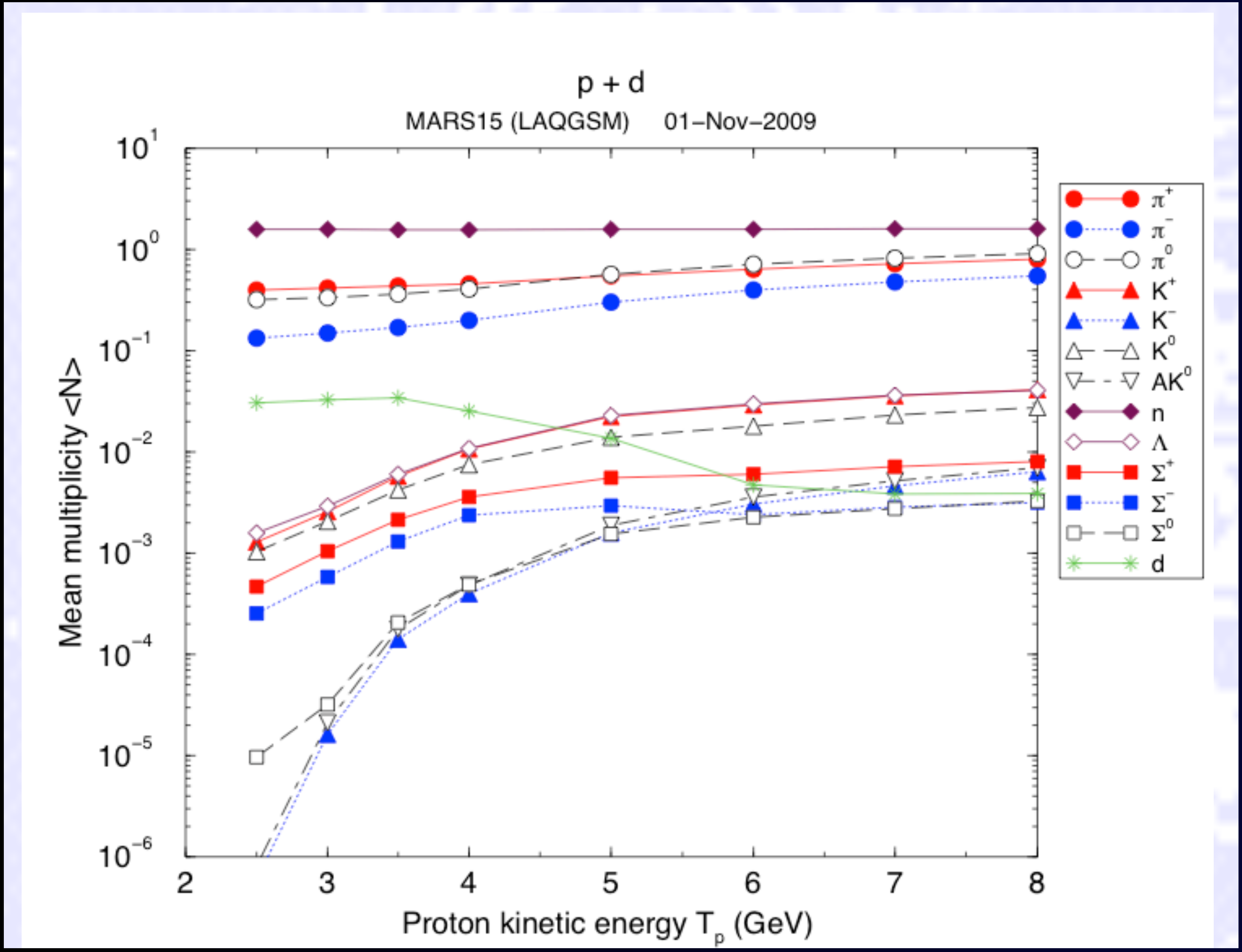
$$\text{K production (<1 GeV):}\quad \frac{\sigma_K^{2\ \text{GeV}}}{\sigma_K^{24\ \text{GeV}}} \sim \frac{1}{30}$$

$$\text{p beam intensity:}\quad \frac{\text{ICD-2}}{\text{AGS}} \sim 300$$

$$\text{K flux:}\quad \frac{\text{ICD-2}}{\text{AGS}} \sim 10$$

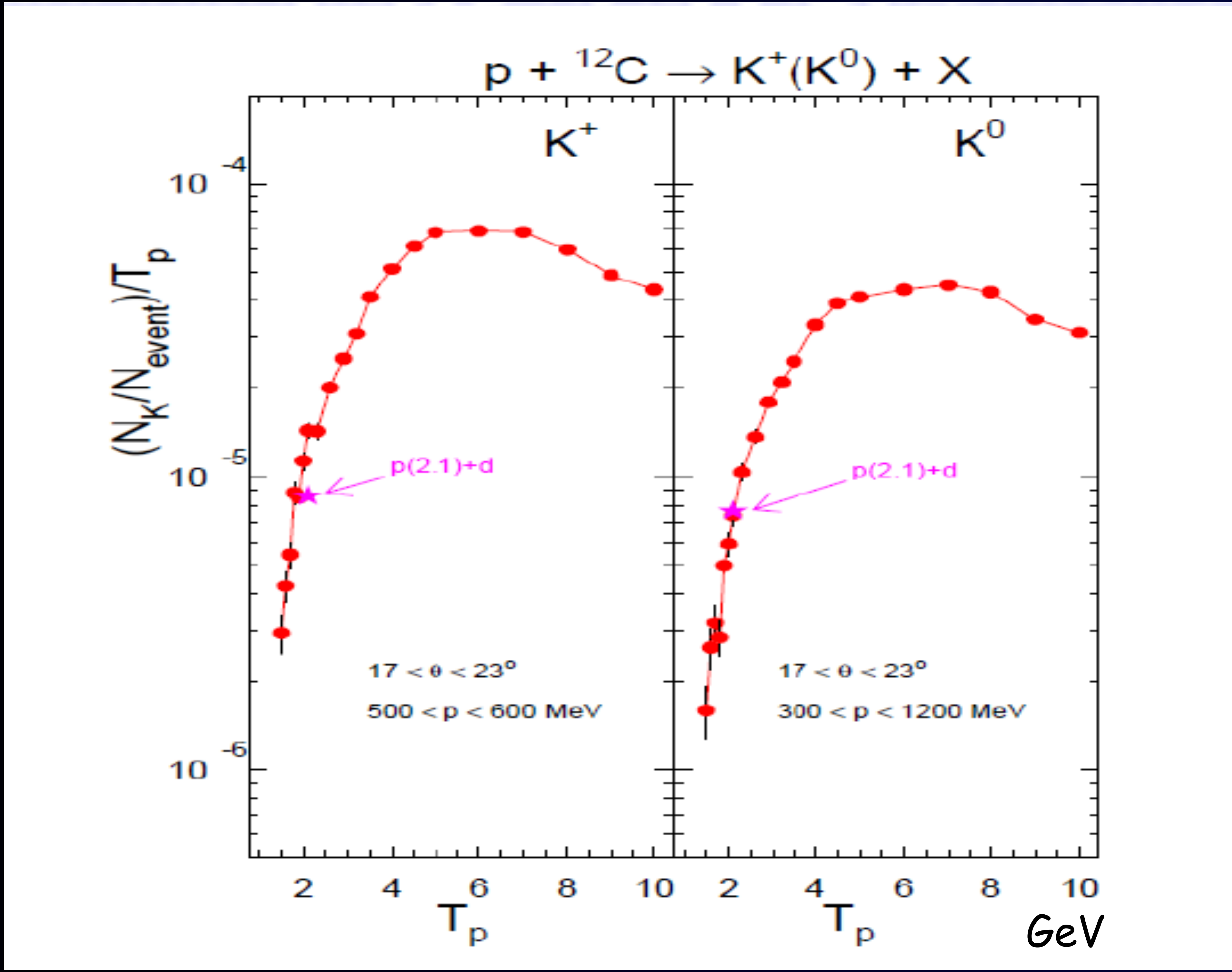
Bryman

IC2 is high power, but what about kaon yields ?



Mokhov&
Gudima

IC2 Kaon yields at constant beam power for stopping K+ and TOF-based KL experiments



Optimum Energy for Stopped and Slow Kaon Experiments

- T_p=4-8 GeV. 1000 event plausibility begins around 2.6 GeV.

- For pure K^0 experiments: T_p=2.6-3.0 GeV. Potentially of great interest for $K^0 \rightarrow \pi ee$ experiments [Nguyen]

- What's the cost? IC2 is a $1B class facility (DOE TPC accounting) Raising the IC2 beam energy by 500 MeV increases the TPC by about 8%.

Recommend T_p=2.6 GeV with upgrade option to 2.9 GeV.

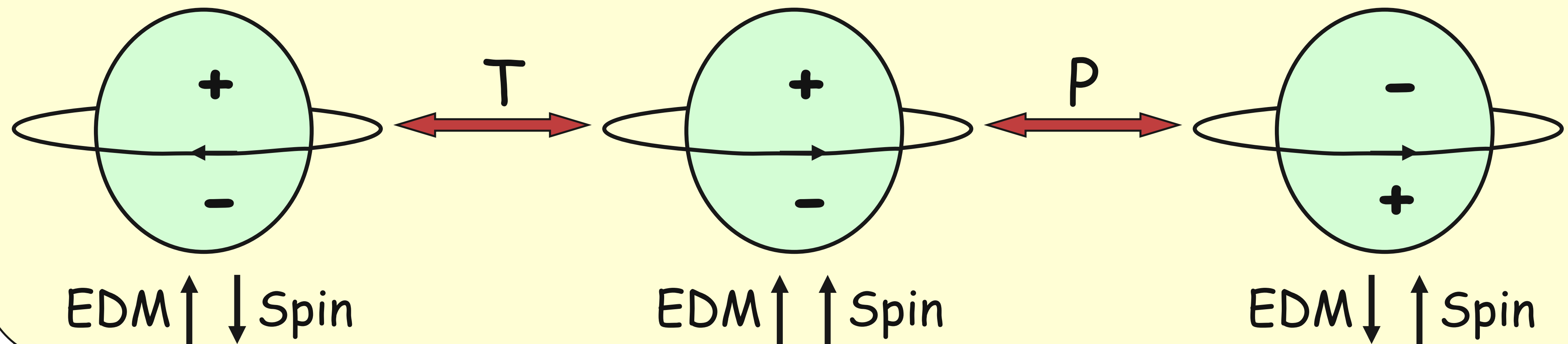
Standard Model via Nuclear Physics

Standard Model via Nuclear Physics

- A high beam power is required to produce radioactive nuclei.

Search for an electric dipole moment and physics beyond the standard model

A permanent EDM violates both time-reversal symmetry and parity

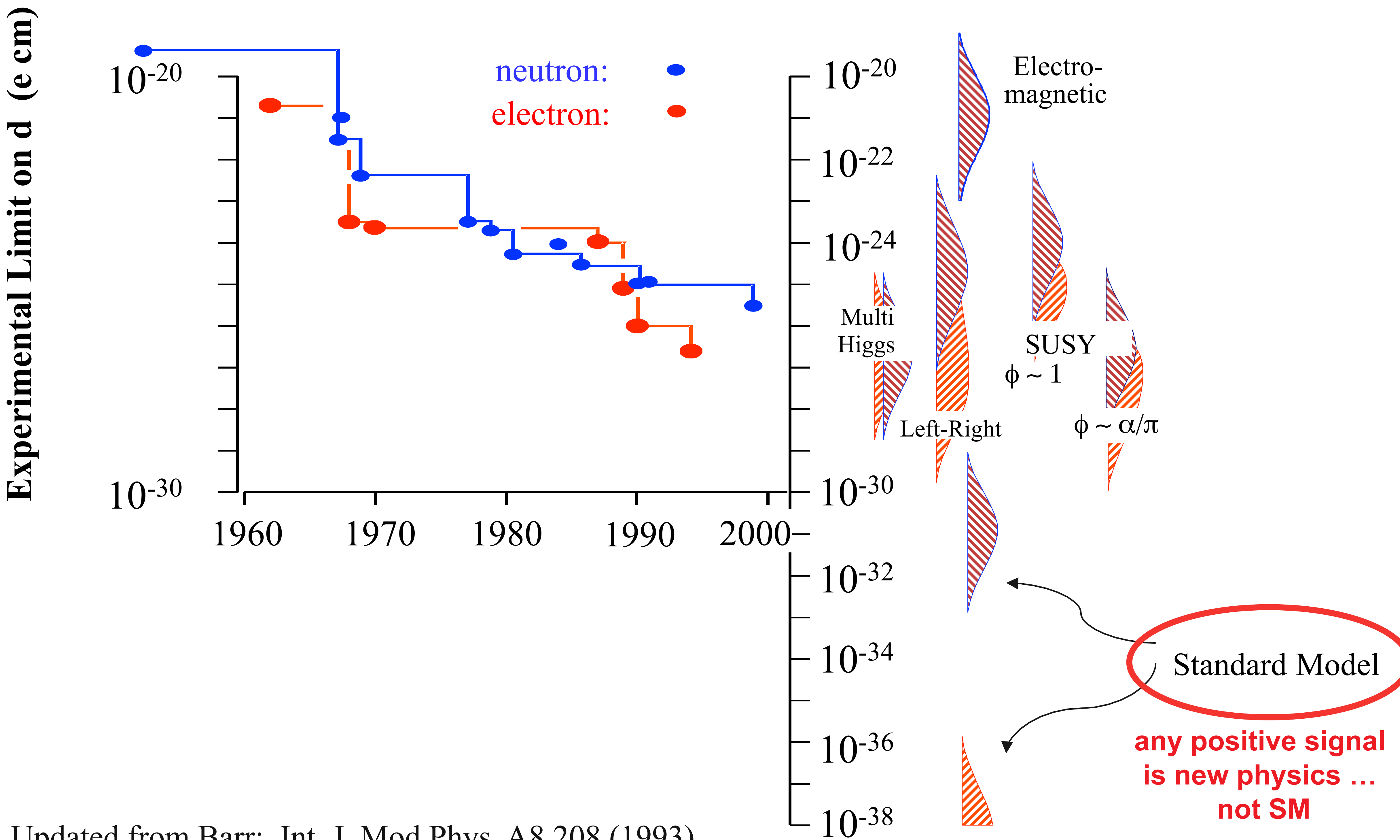


To understand the origin of the symmetry violations, you need many experiments!

- Neutron → Quark EDM, Quark Chromo-EDM
- Diamagnetic Atoms (Hg, Xe, Ra, Rn) → Quark Chromo-EDM
- Paramagnetic Atoms (Tl, Fr) Molecules (PbO) → Electron EDM

Quark EDM, Quark Chromo-EDM, Electron EDM → Physics beyond the Standard Model: SUSY, Strings …

EDM measurements: the SM extension slayers



any positive signal is new physics … not SM

Updated from Barr: Int. J. Mod Phys. A8 208 (1993)

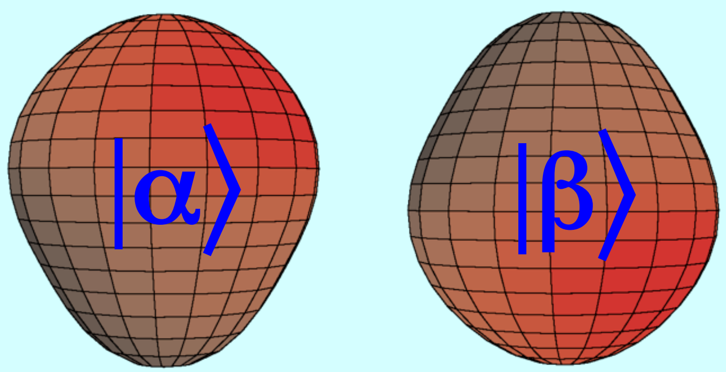
Enhanced EDM of ^{225}Ra

Enhancement mechanisms:

- Large intrinsic Schiff moment due to octupole deformation;
- Closely spaced parity doublet;
- Relativistic atomic structure.

Haxton & Henley (1983)
Auerbach, Flambaum & Spevak (1996)
Engel, Friar & Hayes (2000)

Parity doublet



$$\Psi^- = (|\alpha\rangle - |\beta\rangle)/\sqrt{2}$$

55 keV

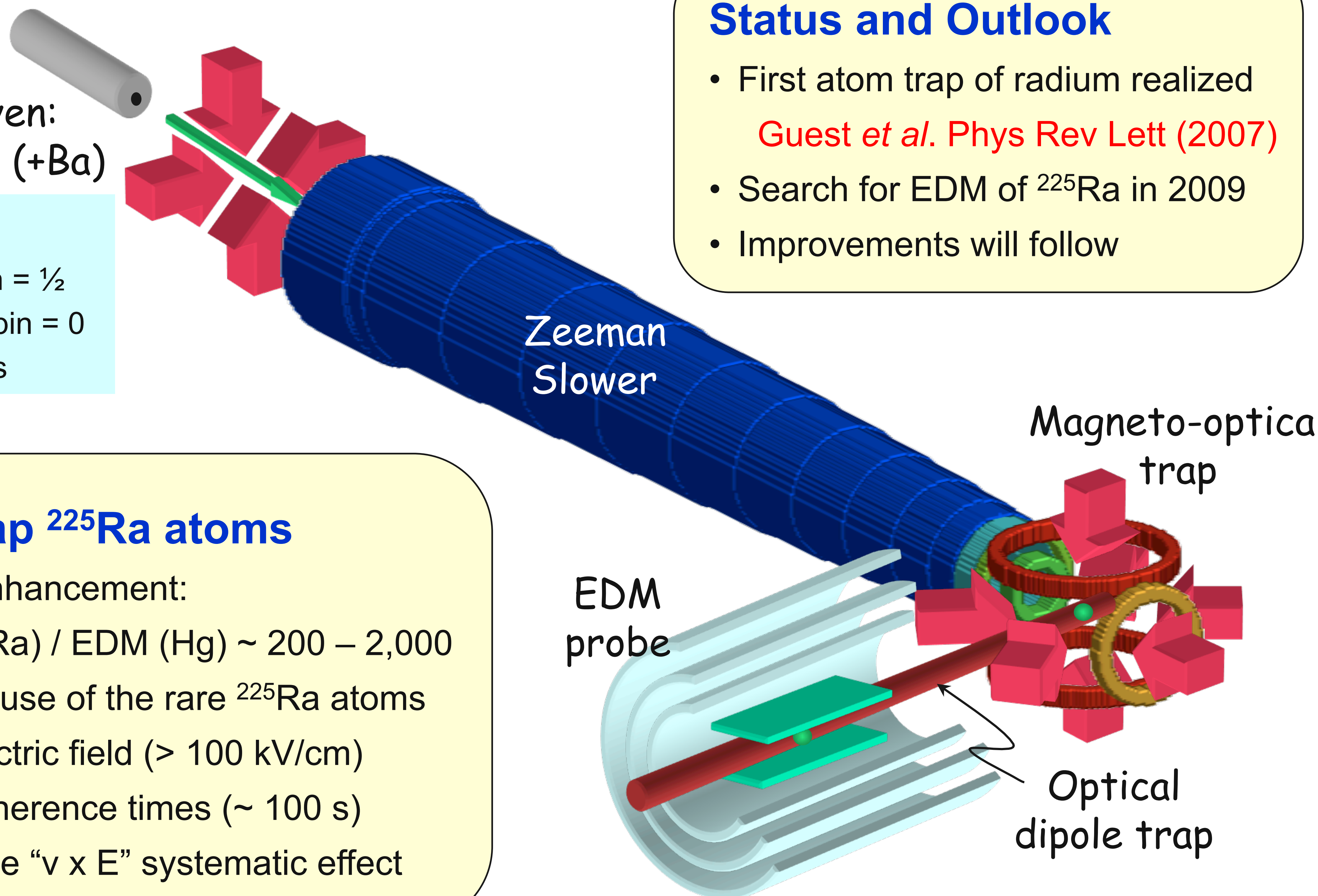
$$\Psi^+ = (|\alpha\rangle + |\beta\rangle)/\sqrt{2}$$

Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

Skyrme Model	Isoscalar	Isovector	Isotensor
SkM*	1500	900	1500
SkO’	450	240	600

Schiff moment of ^{199}Hg, de Jesus & Engel, PRC (2005)
Schiff moment of ^{225}Ra, Dobaczewski & Engel, PRL (2005)

A proposed path for higher sensitivity: EDM of ^{225}Ra at Argonne (Z.T. Lu et al.)



^{225}Ra
Nuclear Spin = ½
Electronic Spin = 0
$t_{1/2}$ = 15 days

Status and Outlook

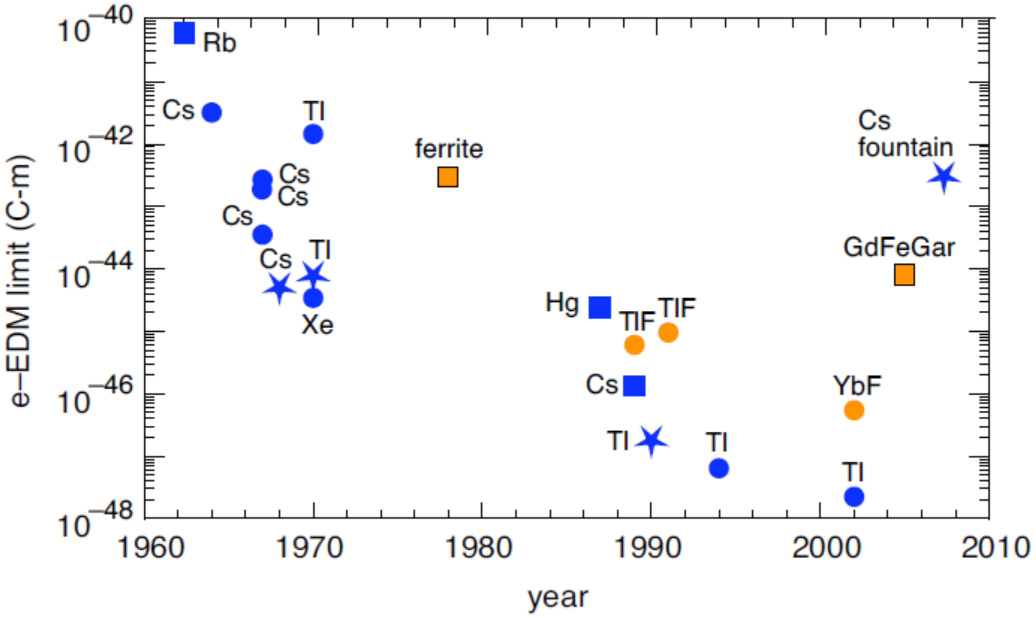
- First atom trap of radium realized
  Guest *et al*. Phys Rev Lett (2007)
- Search for EDM of ^{225}Ra in 2009
- Improvements will follow

Why trap ^{225}Ra atoms

- Large enhancement:
  EDM (Ra) / EDM (Hg) ~ 200 – 2,000
- Efficient use of the rare ^{225}Ra atoms
- High electric field (> 100 kV/cm)
- Long coherence times (~ 100 s)
- Negligible "v x E" systematic effect

A proposed path to improve the e-EDM measurement

- **Best limit on the e-EDM comes from measurements with an atomic beam of Tl**
  - ***7 orders of magnitude improvements in 50 years***
  - ***No improvements in the last 7 years***
- **New technology needed → atomic fountains**
  - **Demonstrate feasibility with Cs**
  - **Obtain best limit with Fr (9 times more sensitive to e-EDM)**
    - ***Fr production with 500 kW of 2 GeV protons would give a factor 100-1000 gain in Fr production over any existing facility***



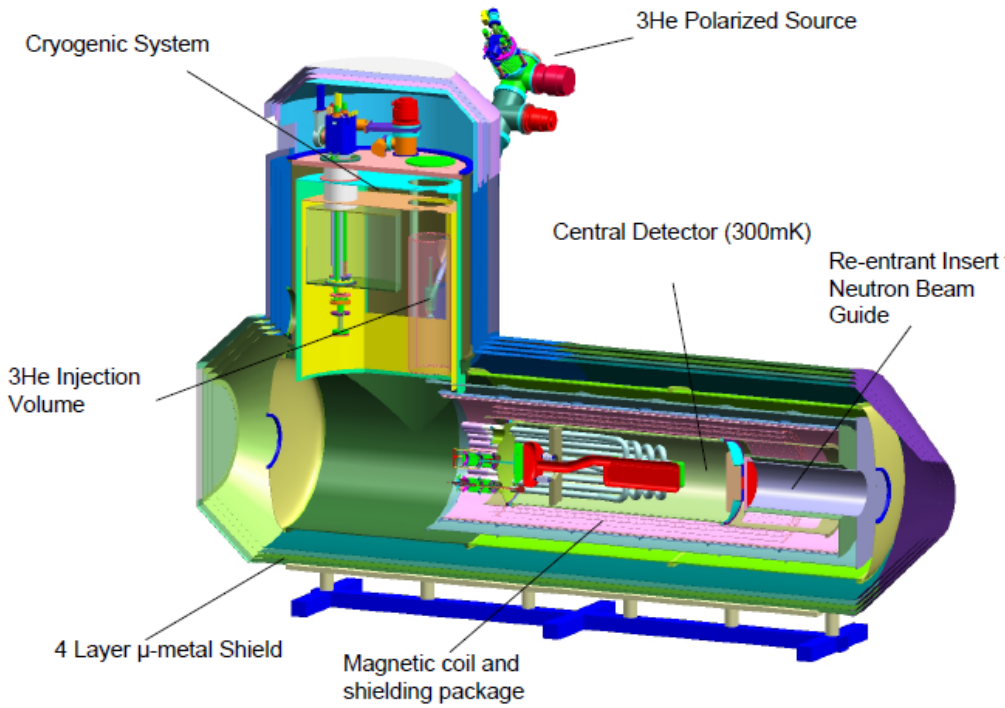
Experimental upper limits to the e-EDM 1962-2009

Proof-of-principle atomic fountain EDM experiment
Photo courtesy of H. Gould

n-EDM searches … intense UCN sources needed

- Large n-EDM experiment in preparation in the US at the SNS
- UCN offer unique advantages for these studies and there is intense activity worldwide to create stronger sources
- A few % of the 500 kW proton beam could provide a cutting edge facility for such studies in the US

nEDM Experiment at the SNS



Source	Type	Ec (neV)	ρ_{UCN} (UCN/cm3)	Status	Purpose
LANL	Spallation/D2	180	35	Operating	UCNA/ Users
ILL	Reactor/ turbine	250	40	Operating	n-EDM/ Users
Pulstar	Reactor/D2	335	120	Construction	Users
PSI	Spallation/D2	250	1,000	Construction	n-EDM
TRIUMF	Spallation/ HE-II	210	10,000	Planning	n-EDM/ Users
Munich	Reactor/D2	250	10,000	R&D	Gravity
SNS	n beam/HE-II	130	400	R&D	n-EDM

US/Fermilab Strategy at the Energy/Intensity Frontier

Energy Frontier

Intensity Frontier

Tevatron Collider (FY2012)

(LHC)

ILC, Muon

protons

technology

technology

injector

NuMI (260kW) Booster

NuMI (700kW) (FY2013)

Project X 2 MW (120GeV) for ν + 2MW(2GeV) + 200kW(8GeV)

injector

ν Factory

MINOS
MiniBooNE
SciBooNE
ArgoNeuT

NOvA
MINERvA
MicroBooNE

1300km baseline ν
DUSEL WC / LAr
(+Proton Decay,..)

Mu2e
μ g-2
K^+

Mu2e II
μ g-2 II
$(K^0/K_L, K^+)$ II
EDM (μ, Λ, Σ^+) II
Nuclear Physics
....

This workshop is about this physics

White Paper on Physics with Project X

time

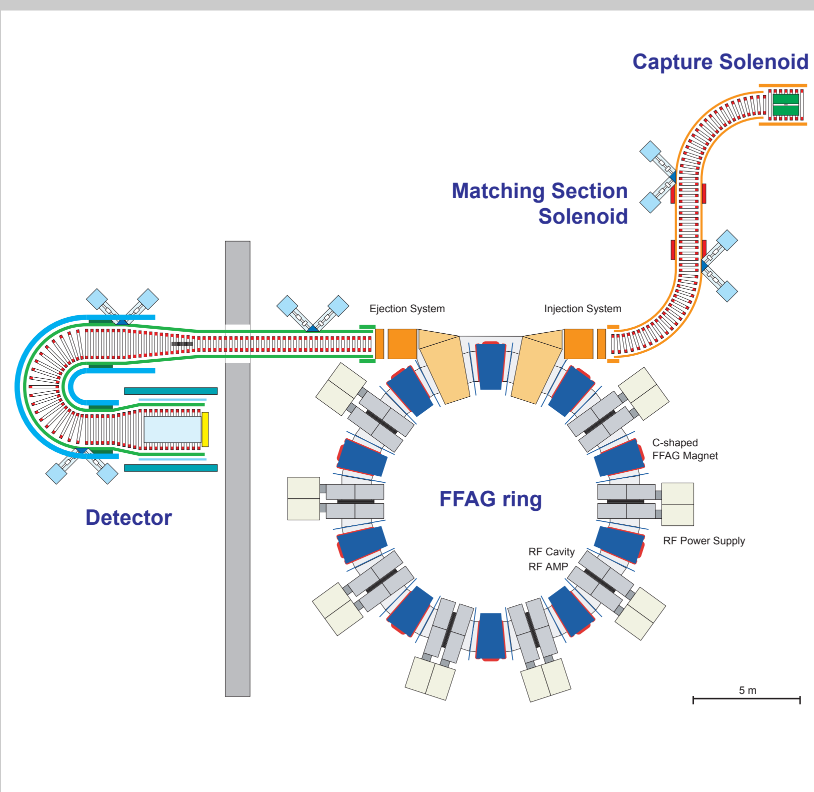
Roadmap of Particle Physics based on muons

2002

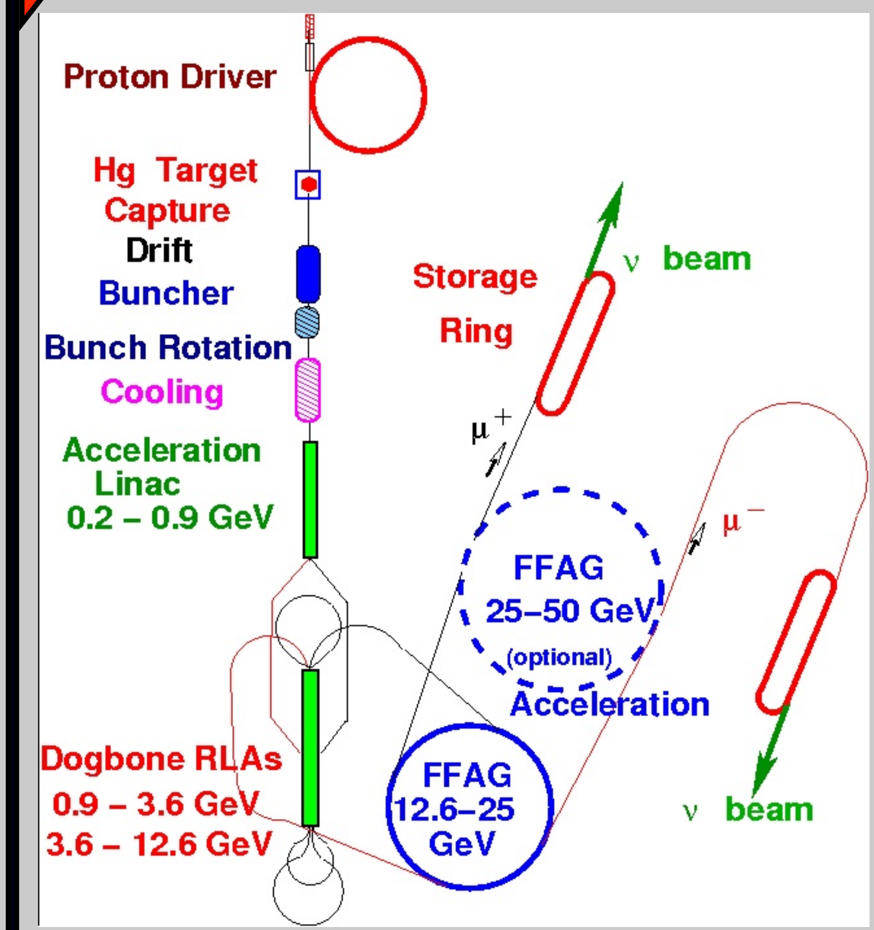
Based on common technologies

Muon Factory

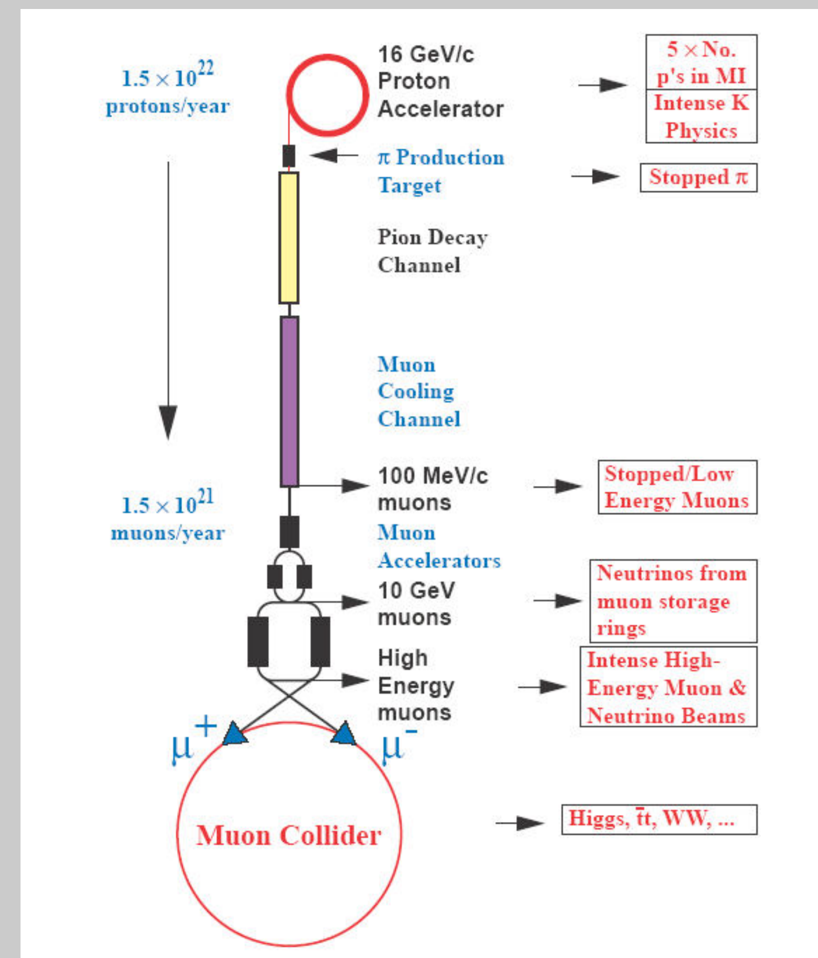
muon LFV,
muon g-2,
muon EDM
muon application



Neutrino Factory



Energy frontier Muon Collider - 2~4 TeV



Summary

Project-X IC2 would provide diverse and significant physics programs at the high intensity frontier.